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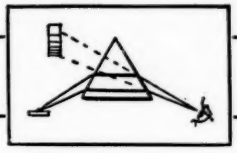

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Journal of the
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The Search for High Efficiency Light Sources*

SAUL DUSHMAN
General Electric Company, Schenectady, New York
(Received November 24, 1936)

THE search for high efficiency light sources began with the invention by Edison in 1879 of the carbon-filament lamp. During the subsequent period, physicist, physical chemist, metallurgist, glass chemist, electrical engineer and illuminating engineer, along with the manufacturer and production engineer, have cooperated constantly toward the development of more and more efficient light sources which would at the same time be both more practical and less expensive. The history of this development, which has resulted in one of the most important industrial activities of our age, is filled with many episodes which are of great scientific interest, aside from their subsequent commercial development. I need mention only one such episode, the observation made by Edison on the production of blue glow in lamps, which led, as is well known, to the development of the vacuum tube and radio-communicating industries.

In the following summary of the present status of investigations in the field of light sources, the subject is discussed mainly from the point of view of the physicist. Thus, the reader will find little or no mention of the technical applications or of those electrical characteristics which are of importance from the point of view of the illuminating engineer. Furthermore, a large number of special types of discharge lamps have not been described, since such information is available in many of the publications to which references are given in the bibliography at the end of the paper.†

LUMINOUS EFFICIENCY

In any consideration of light sources it is first of all necessary to take into account the characteristics of the human eye as a detector of radiation. Fig. 1 shows some typical line spectra and the visibility curve.[28, 85] There are also given values of the visibility factor V_λ for the most intense lines in these spectra. The light output L, in *lumens*, is given by the relation

$$L = 621 \int_0^\infty V_\lambda E_\lambda d\lambda, \qquad (1a)$$

where E_λ is the energy distribution function for the source in watts per cm² per unit wave-length. For all practical purposes V_λ may be taken as zero for all wave-lengths outside the region included between $\lambda_1 = 4100$A and $\lambda_2 = 7200$A. A monochromatic source of radiation, emitting only the radiation $\lambda = 5550$A, would emit light at an efficiency of 621 lumens per watt, and for any source for which the mean visibility is $\bar{V}_\lambda$,

* This article is based upon a paper presented by invitation at the meeting of the Optical Society in New York, October 30, 1936.

† These references are indicated by corresponding numbers in the bibliography.

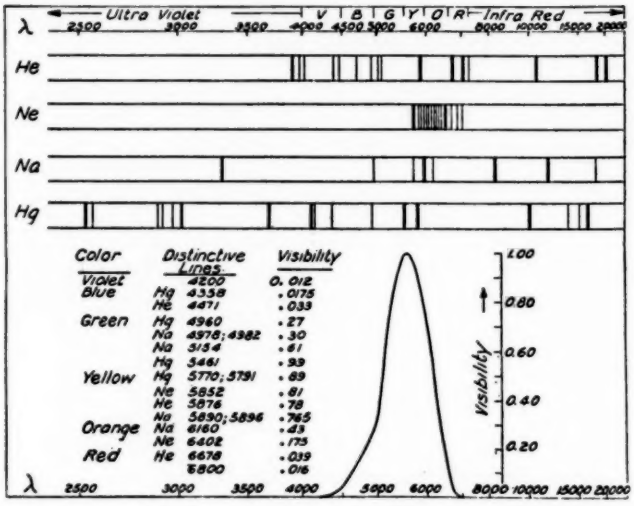

FIG. 1. Some typical line spectra and visibility curve.

the lumen output per unit area is given by

$$L = 621\,\bar{V}_\lambda \int_{\lambda_1}^{\lambda_2} E_\lambda d_\lambda. \tag{1b}$$

The *specific luminous efficiency* of a source is defined by the relation

$$L_s = L/W, \tag{2}$$

where W is the total energy input in watts and L is the total lumens emitted.

For any given source the energy radiated in the visible range is a fraction η of the total energy W. The *optimum luminous efficiency* L_0 of such a source is defined by the relation

$$L_0 = L/(\eta W). \tag{3}$$

Thus, L_0 is a measure of the maximum light output which could be obtained from a *fictitious* source emitting the *same color* of light, but emitting no radiation whatever outside the visible range.

Finally, the *energy utilization ratio*‡ ϵ for any source is given by the relation

$$\epsilon = \frac{\int_0^\infty V_\lambda E_\lambda d\lambda}{W} = \frac{L}{621W} = \frac{L_s}{621}. \tag{4}$$

‡ In previous publications by the writer (see references 43 and 47) this expression has been used to designate the ratio η. Subsequent consideration has led to the conclusion that it would be more logical to designate the ratio ϵ as the energy utilization ratio.

Table I gives data on the values of L_s, L_0, η and ϵ for a number of light sources. The values of L_s are those observed on actual lamps, while the values of L_0 have been derived on the basis of mean values of V_λ for the different colors.

TABLE I. *Luminous efficiencies of various sources of light (lumens per watt). For spectral energy distribution data see references 28, 29a, 29b and 41. Methods of measurement and data are discussed comprehensively in reference 37.*

SOURCE	L_0	L_s	100η	100ϵ
BLACK BODY AT T = 6500	218	86.3	39.5	13.9
SUN	250[a]	100	40	16.1
TUNGSTEN (GAS-FILLED)	143[a]	15–30	10 –20	2.5– 5.0
FLAMING ARC	220	45–75[b]	20 –34	7.2–12.1
SODIUM VAPOR	475[c]	50–75	10 –15	8 –12
MERCURY VAPOR				
LOW PRESSURE	248[d]	15–20	6 – 8	2.5– 3.2
1 ATM. (TYPE H)	298[a]	30–35	10 –12	4.8– 5.6
HIGHER PRESS.	298	40–50	13 –17	6.4– 8.0
NEON	198[d]	15–40	7.5–20	2.5– 6.4
HELIUM		4–10		
CARBON DIOXIDE		2– 4		
CADMIUM		0.5– 1		
GREEN FLUORESCENT (L.P. MERCURY)	475[e]	60–80[f]	12.6–16.9	9.6–12.9

[a] Value given by L. J. Buttolph, reference 41.
[b] A. C. Downes, Elect. Eng. **54**, 761 (1935), states that efficiencies as high as 79 L/W have been obtained.
[c] Based on V_λ for D lines.
[d] Value calculated by F. A. Benford from energy distribution.
[e] Calculated from energy-distribution data obtained in this laboratory by G. R. Fonda.
[f] Values obtained by G. E. Inman, Incandescent Lamp Division, General Electric Co., Cleveland, Ohio.

Incandescent Solids as Light Sources[1, 28]

The ideal radiator from the point of view of general illumination would be a source emitting "white" light, that is, light of the same color as "daylight" and having a continuous spectrum over the visible range. However, here we meet with considerable difficulties, due not only to the fact that no artificial source is available for the production of such radiation but also to the lack of agreement on what constitutes "daylight illumination."[32] The nearest approach to such a hypothetical source is a "black-body" radiator at a temperature between 5000 and 6000 deg. K. Table II shows the radiation characteristics of such a source for a range of temperatures.

Fig. 2 shows the energy distribution for a black-body radiator at 5000 and 6000 deg. K. The shaded area gives the fraction of the energy at 6000 deg. K. observed as visible light. It thus corresponds to the area given by the value

$$\int_{\lambda_1}^{\lambda_2} V_\lambda E_\lambda d\lambda.$$

According to H. E. Ives[84] the maximum efficiency of solar radiation is 86.5 lumens per watt, which, as is shown in Table II, corresponds to that of a black body at 6500 deg. K. This would give for L_0 in the case of white light, thus defined, a value of 218.5 lumens per watt, while if we define white light as a source having constant value of E_λ in the visible range (as is shown by the rectangle ALNB in Fig. 2), the value of the optimum luminous efficiency would be 217.4 lumens per watt and the utilization factor would be 0.35. (This is the ratio of the shaded area to that of the rectangle.)

Under these conditions it has seemed best to

Table II. *Total energy and luminous characteristics of a black-body radiator.*

T Deg. K	W Watts Per cm²	L Lumens Per cm²	L_s Lumens Per watt	L_0 Lumens Per watt	η
2000	91.4	1.40×10^{2}	1.53	153	0.01
3000	426.4	8.89×10^{3}	19.2	206.7	0.093
4000	1462	7.32×10^{4}	50.1	219.6	0.228
5000	3570	2.64×10^{5}	73.9	229.3	0.322
5500	5226	4.22×10^{5}	82.6	227.9	0.362
6000	7403	6.22×10^{5}	84.0	221.1	0.380
6500	10190	8.75×10^{5}	86.3	218.5	0.395
7000	13710	11.53×10^{5}	84.1	212.9	0.395

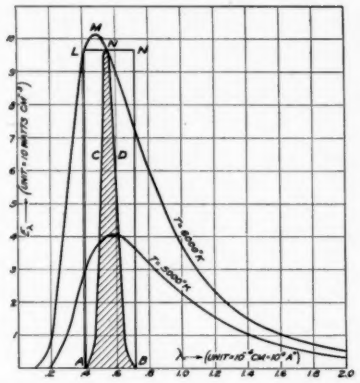

Fig. 2. Energy distribution for a black-body radiator, showing fraction emitted as visible light at 6000 deg. K.

the writer to assume that for all practical purposes the value of L_0 for white light may be taken as 220 lumens per watt.

As a practical source of continuous radiation emitting light of a color approaching that of daylight, we have available the tungsten filament operating in gas-filled lamps at temperatures as high as 3400 deg. K., which is within 250 deg. of the melting point of the metal. The radiation characteristics of tungsten have been described by W. E. Forsythe and A. G. Worthing,[2] and by H. A. Jones and I. Langmuir.[3]

Fig. 3 shows for comparison plots of brightness *versus* temperature for a black-body radiator and for tungsten, and a plot of L_s for the latter. The luminous efficiencies and operating temperatures of the standard types of gas-filled tungsten lamps have been measured by W. E. Forsythe and his associates,[4] and a few of the results are indicated by isolated points in Fig. 3.

In view of the fact that the value of L_s for tungsten at the melting point (3665°K) is approximately 53 lumens per watt, it is evident that the possibility of any radical increase in the efficiency of tungsten lamps is rather remote.[55] The only manner in which we could obtain higher efficiencies from incandescent solids would be by the use of materials of higher melting point. A number of years ago it was observed that some carbides and nitrides have very high melting points. Such a compound, which has about the highest melting point observed so far (4150°K) is TaC.[34, 53] However, up to the present it has

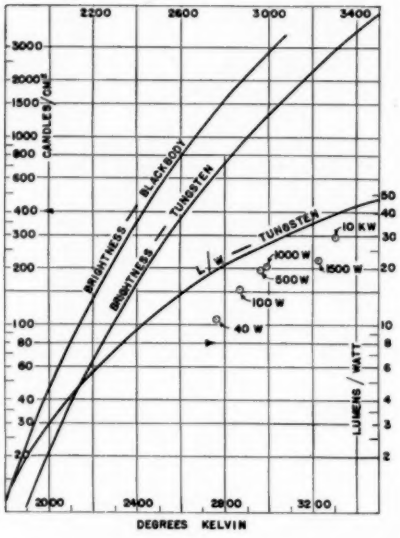

FIG. 3. Brightness of black-body and tungsten, and efficiency of tungsten as functions of temperature.

not been found possible to utilize this material in a practical type of lamp, the main reason being the dissociation of the carbide and consequent fusion of the tantalum.

From time to time attempts have been made to utilize refractory oxides such as ZrO_2 and ThO_2. However, as is well known, the selective emissivity of these substances in the visible region, decreases with increase in temperature,[1] and near their melting points (which are lower than that of tungsten) their emission characteristics are no better than those of tungsten or tantalum.

LUMINOUS EFFICIENCIES OF ELECTRIC DISCHARGES IN GASES AND VAPORS

The cold cathode neon tube and the low pressure mercury vapor discharge lamp have been utilized for many years in special fields of illumination. While the luminous efficiencies of these sources are comparable with those of incandescent lamps, there have been developed in recent years hot cathode discharge lamps using sodium vapor, neon, or mercury, which are much more efficient. The light emitted exhibits a line spectrum which is characteristic, in each case, of the gas or vapor used (as shown in Fig. 1), and consequently the color is more or less monochromatic. Furthermore, the electrical characteristics of these discharge lamps are radically different from those of incandescent lamps, so that the two types of lamps require different forms of electrical circuits.

As shown in Table I, the luminous efficiencies actually observed with practical discharge lamps are two to three times those obtained with similar wattage tungsten lamps. However, the energy utilization ratio ϵ is low even in the best cases. From the point of view of the physicist the problems of interest are those regarding the mechanism of light production in these discharges and the fundamental causes for the low values of the energy utilization ratios which are observed.

In any consideration of this type of lamp, it is necessary to recognize that the light emitted is a by-product of the electrical phenomena in the discharge. The fundamental processes consist in the collision of electrons with the atoms of the gas or vapor. These collisions result in the formation of excited atoms and ions. The latter serve to eliminate electron space charge at the cathode and thus make it possible for the discharges to operate at appreciable current densities. The nature and concentrations of the excited states govern the type of spectrum emitted and the intensities of spectral lines, that is, the type of atom used governs the color of the light emitted. It would therefore seem logical to discuss the phenomena in electric discharge lamps from two points of view: (1) that of the mechanism of light production in a gas; (2) that of the electrical transport phenomena involving electrons and positive ions.

ORIGIN OF SPECTRAL LINES: CRITICAL POTENTIALS

It is hardly necessary to mention that our present views on the origin of spectral lines are based on the concept first postulated by N. Bohr in 1913, that the emission or absorption of light of definite frequency ν by an atomic (or molecular) system is due to a transition of the system from a state i, having an energy E_i, to a state f, having an energy E_f. If E_i is higher than

E_f, the frequency emitted is given by the relation

$$\nu = (E_i - E_f)/h. \quad (5)$$

The actual values of the different possible energy states for any particular atom may be determined either from an analysis of the spectrum or by experiments of the type initiated by Franck and Hertz, and at the present time we have a vast amount of data, which have been accumulated during the past two decades, on the energy states of nearly all the elements.[8, 9, 12] For our purpose it is most convenient to designate the energy states or "levels" in terms of the potential difference through which an electron would have to be accelerated in order that a collision with the atom would result in the formation of any

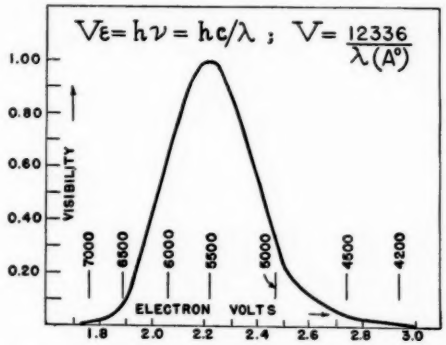

FIG. 4. Visibility curve as function of electron volts.

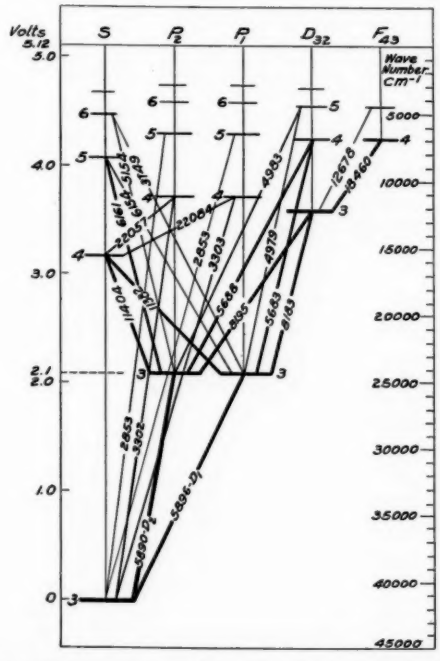

FIG. 5. Energy levels and lines in arc spectrum of sodium.

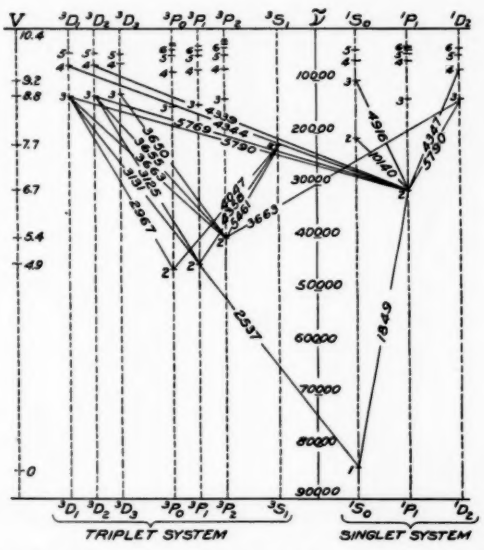

FIG. 6. Energy levels and lines in arc spectrum of mercury.

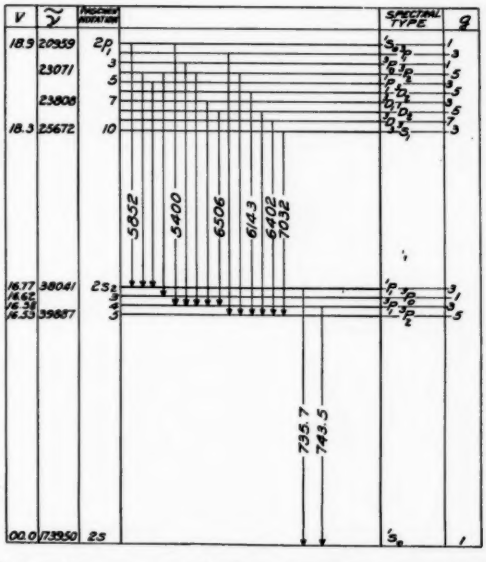

FIG. 7. Lower energy levels and lines in arc spectrum of neon.

TABLE III. *Critical Potentials, Resonance Lines, and Metastable Levels*

ATOM	V_r	λ_r	V_m	V_i
LITHIUM (Li)	1.84	6,708		5.37
SODIUM (Na)	2.10	5,890; 5,896		5.12
POTASSIUM (K)	1.60	7,645; 7,699		4.32
RUBIDIUM (Rb)	1.56	7,800; 7,948		4.16
CAESIUM (Cs)	1.38; 1.45	8,521; 8,943		3.87
HELIUM (He)	20.91	592	19.77	24.47
	21.12	584	20.55	
NEON (Ne)	16.58	744	16.53	21.47
	16.77	736	16.62	
ARGON (A)	11.56	1,067	11.49	15.69
	11.77	1,048	11.66	
KRYPTON (Kr)	9.98	1,236	9.86	13.94
	10.59	1,165	10.51	
XENON (Xe)	8.39	1,469	8.28	12.08
	9.52	1,295	9.40	
ZINC (Zn)	4.01	3,076	3.99	9.36
	5.77	2,139	4.06	
CADMIUM (Cd)	3.78	3,261	3.71	8.96
	5.39	2,288	3.93	
MERCURY (Hg)	4.87	2,537	4.64	10.38
	6.67	1,850	5.44	
THALLIUM (Tl)	3.27	3,776	0.96	6.07
	4.46	2,768		

given excited state. If we write Eq. (5) in the form

$$h\nu = (V_i - V_f)\epsilon = V\epsilon, \tag{6}$$

and convert to ordinary volts, then we obtain the relation

$$\nu = 8106\, c.V, \tag{7}$$

where c = velocity of light, or in terms of wave number,

$$\bar{\nu} = 8106\ V. \tag{8}$$

Expressed in terms of the wave-length corresponding to this transition, the last relation assumes the form

$$\lambda = (12336)/V. \tag{9}$$

In these last three equations we designate the magnitude V as the electron volts (ev) corresponding to the given monochromatic radiation.

The electron volts corresponding to the limits of visibility are consequently 1.8 and 2.9, and Fig. 4 shows the visibility curve plotted against electron volts instead of against λ. Thus, in order to obtain visible light we must have transitions which range between 1.8 and 2.9 ev.

Figs. 5, 6 and 7 show the energy level diagrams for sodium, mercury and neon, respectively. As shown in Table I, these elements are the most interesting from the point of view of practical light sources. Table III gives values of V_i, the ionization potential, V_r, the *resonance* potential, and λ_r, the wave-length of the *resonance* line, for these atoms and a few of the other elements. The column headed V_m gives the electron volts corresponding to the *metastable* levels.

When we examine the energy level diagrams of the three elements Na, Hg and Ne, it is seen that in the case of Na it is possible to convert 2.1 ev directly into photons of visible light. On the other hand, in the case of Ne and Hg the atoms have to be excited to levels which are above the resonance levels. Consequently, the electrons have to acquire an energy of about 19 ev before atoms of neon can be excited to a state from which such transitions are possible as will yield visible radiation. Therefore, it would appear that at the maximum we could not expect an efficiency of light production from neon, greater than about $2.2/19 = 1/9$ of the optimum possible, that is, about 22 lumens per watt. Similarly, in the case of mercury, we would expect at the maximum an efficiency of about 2/8 of the optimum, or about 50 lumens per watt.

Actually, as Table I shows, the values of L_s observed for neon is almost twice the value deduced above. The existence of this and similar observations shows that there are additional factors which govern the efficiency of light production. It is these other factors which we must therefore consider in the following sections.

PROBABILITY OF EXCITATION AND IONIZATION

The intensity of any spectral line depends in the first place upon the rate at which transitions occur from some excited state k to a lower state j. Under stationary conditions, the rate at which atoms in state k revert to state j will be equal to the rate at which they are formed. Therefore, the intensity of light must vary with both the electron current (I_e) and the concentration of atoms in the lower state j, (N_j), since the number of collisions per unit time, per unit volume will vary with the product $N_j \cdot I_e$. However, not all collisions between sodium atoms and electrons of kinetic energy 2.10 volts (or higher) are effective

in producing excited atoms in the $3P$ state. The probability is a function of the velocity (or kinetic energy) of the electron. It is customary to define the *probability of excitation* P_e[14] as the number of excited atoms formed per unit electron current, per unit length of path, per unit pressure at zero deg. C. The manner in which P_e varies with V (i.e., with the kinetic energy of the electron) is characteristic of each energy level.

For instance, in the case of the $3P$ state of sodium the maximum value of P_e occurs at 2.5 volts, approximately, while in the case of the 2^1P_1 state of mercury, P_e increases from zero at 6.67 volts (the value of V_r) to a maximum at 6.8 volts.

In a similar manner, the *probability of ionization* P_i[14] is defined as the number of ions formed per unit electron current, per unit path length, per unit pressure at 0°C. For values of V less than $4V_i$, P_i increases linearly with V according to a relation of the form

$$P_i = C(V - V_i), \tag{10}$$

and from the results obtained by I. Langmuir and H. A. Jones[11] and other investigators it is possible to determine the values of the constant C in the above equation.

A number of years ago R. Seeliger[5] suggested the concept of *optical excitation function* F_e, which gives the intensity of any spectral line as a function of the kinetic energy of the incident electron. A great deal of work has been carried out by W. Hanle and K. Larché[22] on the experimental determination of this function for a number of spectral lines.

If the probability of a transition from state k to state j is designated by A_{kj}, then it is evident that

$$F_e = P_e A_{kj}, \tag{11}$$

so that F_e is intimately related with the probability function for excitation.

Each of the functions P_e and P_i determine a mean free path which is different from the values of L_0, the kinetic theory mean free path for electrons under standard conditions of pressure and temperature. Consequently, L_0P_e or L_0P_i are to be regarded as measuring the probability that excitation or ionization, respectively, will occur at any one collision between the electron and atom. This probability is a function of the kinetic energy of the electron and its magnitude is obviously of extreme importance from the point of view of light production. For instance, it may be shown[47] that for a 22.0 volt electron in neon, the probability of ionization at a collision is 0.00134, or one collision out of 750 is effective in producing ionization. In the case of the excitation of the $3P$ levels in sodium, the probability that a 2.5 volt electron will cause excitation to this level is about 0.05.

Life of Excited Atoms and Metastable States[10]

In the previous section mention has been made of the Einstein coefficient A_{kj}, which represents the probability of a transition per unit time from state k to state j. The reciprocal τ_{kj} is a measure of the average life of the excited state k with respect to the radiation of frequency ν_{kj}. According to classical electromagnetic theory

$$\tau = 3mc^2/8\pi^2e^2\nu^2 = 1\cdot131\times10^{-8}(\lambda_0/5000)^2 \text{ sec.}, \tag{12}$$

where m = mass of electron; λ_0 = wave-length of radiation; and c = velocity of light.

On the other hand, the quantum theory leads to a relation between the value of τ and the *absorption* coefficient α, for the radiation, which is of the form

$$\alpha = K\cdot n\lambda_0^3/\tau(T)^{\frac{1}{2}}, \tag{13}$$

where K is a constant for the transition k to j; n is the number of absorbing atoms per cm^3, and T is the absolute temperature. It is thus possible to determine τ from measurements of the absorption coefficient for the resonance radiation. From such observations it has been shown that for ordinary excited states, the value of τ varies from 2×10^{-9} to 2×10^{-8} sec. for different cases.

As a consequence the resonance radiation has an extremely small free path in a discharge. For instance, in a sodium vapor discharge with a wall temperature of 230°C, the mean free path for the resonance radiation is about 0.007 cm, so that most of the light is emitted by a film on the inside wall which is only 0.015 cm thick.[44] The radiation generated inside this region is absorbed and reemitted many times before it is finally radiated from the surface of the lamp.

In a previous section mention has been made of the existence of metastable states in the case of all monatomic elements except those of the alkali metal series. A spontaneous transition from these states to the normal, accompanied by emission of radiation, is extremely improbable. The existence of such a low probability of transition would lead to values of τ, the life of the metastable state, which are of a much larger order of magnitude than that observed for the other type of excited state discussed in the previous sections.

However, in a discharge metastable atoms are actually destroyed in an interval ranging from 10^{-2} to 10^{-4} second by one or more of the following processes:[47]

(1) The metastable state may be excited to a higher state by electron bombardment.

(2) The same result may be obtained by absorption of radiation. Thus in the case of neon the atom in the metastable state s_5 can absorb λ6143, λ6402 and λ7032. Similarly, mercury in the $^3P_2$ state can absorb λ5461 and λ3663. In fact observations on the intensity of absorption of λ6402 have been used to determine the concentration of metastable atoms in a neon discharge tube.

(3) The metastable state may be destroyed by collisions of the second kind. For instance, in the case of neon, as shown in Fig. 7, the metastable state s_5 differs in energy from the resonance level s_4 by only 0.05 ev. By collision with a normal neon atom, the atom in state s_5 may acquire sufficient energy to raise it to state s_4 from which a transition to the normal state can occur by emission of the resonance radiation λ743.5.

(4) If there is present an admixed gas whose atoms have an ionization or excitation potential lower than the excitation potential of the metastable state, the atoms in the latter state may transfer energy to the foreign atoms. For instance, in a mixture of neon and argon, the metastable neon atoms ($V_m = 16.53$ and 16.62) can cause ionization of argon atoms ($V_i = 15.69$).

(5) Lastly, the metastable atoms are destroyed by impact on the walls of the discharge tube, probably by causing the emission of secondary electrons from the latter.

Thus, in actual discharges the life of the metastable atoms depends upon the temperature, pressure, current density, and geometrical dimensions. Under these conditions it has been found that τ may be expressed in terms of p, the pressure, by a relation of the form

$$1/\tau = A/p + Bp, \qquad (14)$$

where A and B are constants. The term A/p takes into account diffusion to the walls, while Bp corresponds to the rate of disappearance by all the other processes.

Fundamental Electrical Phenomena in a Discharge[5, 6, 7, 11]

The production of light in the visible range requires, as mentioned already, the excitation of atoms by electrons having a kinetic energy ranging from 2 to 3 ev or slightly higher (in order to obtain conditions for maximum values of the probability of excitation). Furthermore, some of the electrons must be accelerated to much higher kinetic energies in order to produce the ions which are required to eliminate electron space charge at the cathode.

As a result of the development during the past two decades of thermionic cathodes for vacuum tubes, it has been found possible to use similar types of cathodes in electrical discharges in gases without excessive depreciation of the cathodes by positive ion sputtering.

A number of constructions of thermionic cathodes for use in gas discharges have been described by A. W. Hull[16] and other investigators.[35, 50] Besides the filamentary type, inside coated cathodes, with barium oxide-strontium oxide as active material, are used to secure high efficiency of electron emission, and shields are often added to reduce heat losses. It is thus possible to operate oxide coated cathodes in gas discharges at emission efficiencies which are considerably greater than those obtained in vacuum devices.

Since in the following discussion only discharge tubes in which hot cathodes are used will be considered, the classification of these tubes suggested by C. G. Found[44] will be adopted. He classifies them, according to the *geometry* of the containing vessel, into 2 types: (1) *cathodic*, (2) *positive column;* and defines these as follows:

"A cathodic discharge is defined as one which is more or less bulbular in shape and in which the distance between cathode and anode is comparable with the smallest dimension of the bulb.

"A positive column is an elongated tube in which the distance between cathode and anode is several times the diameter."

In general, it may be stated that a cathodic type of discharge operates with a voltage drop which is approximately equal to V_i and may be

as low as V_r (owing to successive impacts). A tungar rectifier is an example of such a discharge, and the more recently developed d.c. low voltage sodium lamp is another example. Such an arc may be started on a comparatively low voltage circuit (less than 110 volts) without any auxiliary voltage "kick."

In a positive column discharge the total voltage drop usually exceeds V_i for the gas, and while the discharge tube may be designed to operate on less than 110 volts, a starting kick or some equivalent device, such as auxiliary electrodes, is necessary. This initial high voltage is needed to overcome the negative charge on the walls which tends to prevent the flow of electrons. The low pressure mercury vapor lamp with mercury cathode, and the hot cathode high current neon tubes are examples of this type of discharge. The positive column sodium vapor neon lamp and high lumen output a.c. sodium lamp developed for use on 6.6 amp. constant current circuits,[42, 45] which are described in a subsequent section, are other examples. The main distinction between the two forms of discharge is in the fact that in the cathodic type all of the energy from the external source of supply is converted into kinetic energy of electrons at the cathode, and, consequently, there is no voltage gradient outside the region of the cathode fall, as in a positive column. In the latter, there is in addition to the cathode fall V_c, a drop in the rest of the tube which varies with the length, other conditions remaining constant.

Cathodic Type of Discharge

Let us now consider what occurs in a cathodic type of discharge. The electrons emitted from the cathode produce ions either directly or by cumulative ionization (that is, by successive electron impacts). This permits more electrons to flow, thus altering the potential distribution between the electrodes until finally a stationary condition is attained in which approximately the whole fall of potential is concentrated in a thin *sheath* close to the cathode. The rest of the space between the electrodes is field-free, so that the concentration of electrons (n_e) in this space must be approximately equal to that of the positive ions (n_p). Such a region has been designated by I. Langmuir as a *plasma* and usually this is also the region in which the generation of light occurs.

It has been shown by Langmuir[17] that if the arc current is less than the thermionic emission from the cathode for zero field, then the sheath is actually a double sheath consisting of an electron space charge next to the cathode and a positive ion space charge next to the plasma. Under these conditions the ratio γ between electron current density I_e and positive ion current density I_p at the cathode is given by

$$\gamma = I_e/I_p = (m_p/m_e)^{\frac{1}{2}}, \tag{15}$$

where m_e and m_p denote the mass of electron and positive ion, respectively. (For neon and mercury the values of γ are 192.5 and 605.6, respectively.) The voltage gradient is zero at both the cathode surface and the edge of the plasma, and the relation between I_e (or I_p), the sheath thickness d, and cathode fall V_c, is given by the space charge equation. For current densities such as are used in practical lamps, the value of d is of the order of 0.01 cm, which, at one millimeter pressure, is considerably less than the free path of the electrons. Consequently, most of the electrons that are accelerated in the cathode sheath retain their energy when they enter the plasma. As they drift through the plasma to the anode, this energy is used up in excitation and ionization of atoms with which they collide.

It has been shown by C. G. Found[26, 44] that for zero-field emission at the cathode, $V_c - V_i$ has a definite value under given conditions of pressure and nature of gas. In those discharges in which cumulative ionization occurs, $V_c - V_m$ will be constant. Since the light production depends upon the magnitude of $V_c - V_i$ (or $V_c - V_m$), it is evident that if this is less than 2 volts, the light output will be low. In order, therefore, to obtain high light output from a cathodic type of discharge, $V_c - V_i$ (or $V_c - V_m$) must be greater than about 2.5 volts. The only method by which this result may be secured, at constant gas pressure, is to increase the positive ion current to the cathode, that is, to decrease the ratio I_e/I_p, below the value γ defined by Eq. (15). This may be accomplished by having the arc current exceed the zero-field emission, since the excess current is then obtained by the action of the field

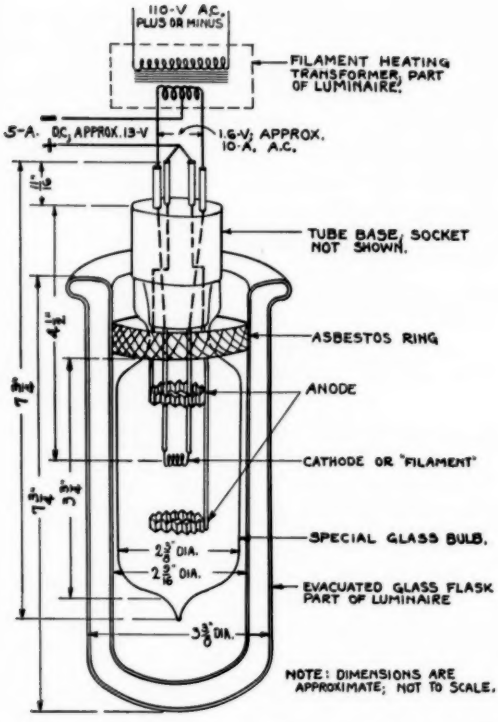
110-V AC. PLUS OR MINUS
FILAMENT HEATING TRANSFORMER, PART OF LUMINAIRE.
5-A. DC, APPROX. 13-V
1.6-V; APPROX. 10-A. A.C.
TUBE BASE, SOCKET NOT SHOWN.
ASBESTOS RING
ANODE
CATHODE OR "FILAMENT"
SPECIAL GLASS BULB.
EVACUATED GLASS FLASK PART OF LUMINAIRE
NOTE: DIMENSIONS ARE APPROXIMATE; NOT TO SCALE.

FIG. 8. 4000 lumen d.c. sodium vapor lamp, showing connections to power source.

established at the cathode by the positive ions. It is therefore evident that in a cathodic type of discharge, the efficiency of light production is determined by the relation between arc current and zero-field emissivity of the cathode.

Let us now consider in further detail the processes which occur in a discharge in a cathodic type of lamp, such as the 4000 lumen d.c. sodium neon lamp[46a] shown in Fig. 8.[46b] The different processes in the discharge are shown diagrammatically in Fig. 9, which is taken from the paper by C. G. Found[44] along with the following remarks.

"In this diagram the energy of the electron has been indicated by the width of the line representing its path. The potential distribution between cathode and anode is shown by the curve, and the energy transformations which take place at the points indicated by numerals are represented by the equations at the bottom. An electron from the hot cathode C is accelerated by the voltage drop in the cathode sheath indicated at 1. Due to the thinness of the sheath, very few collisions will occur within it. As the

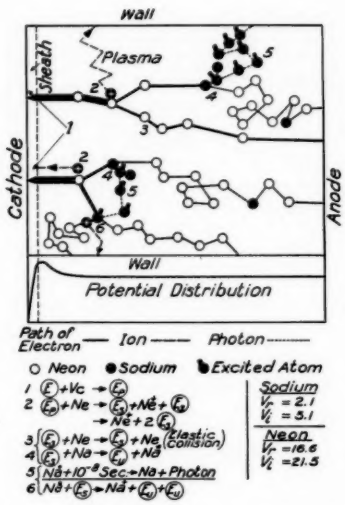

FIG. 9. Processes in a discharge in a mixture of neon and sodium.

primary electron passes through the gas it may collide with either a neon or a sodium atom. However, due to the much greater concentration of neon atoms, it is much more probable that the collision will be with a neon atom. Such a collision may be elastic, as at 2, or it may result in the production of a neon positive ion, as indicated at 3. The production of the ion is accompanied by a loss of energy of the primary electron and the creation of a new secondary electron. In general, the energy of these secondary electrons is much less than the minimum excitation energy for neon. Consequently, it will be impossible for these electrons to transmit any of their energy to neon atoms, except that necessary for the conservation of momentum. These secondary electrons will therefore wander through the tube until one of them finally reaches the anode. However, if the energy of the secondary electron is greater than 2.1 volts, it may cause excitation of a sodium atom. If no neon were present, a collision between an electron and a sodium atom would be extremely rare, since the free path of an electron at this pressure of sodium would be comparable with the dimensions of the tube. However, the presence of the neon greatly increases the effective path of the electron and thereby increases the chance of its collision with a sodium atom. The collision between a secondary electron and a sodium atom, shown at 4, results in the production of an excited sodium atom and a low-velocity or ultimate electron. The excited sodium atom remains in the excited state approximately 10^{-8} sec. and then returns to the normal state accompanied by the emission of sodium-resonance radiation.

"Since the primary electrons have energies greater than the critical potentials of neon, they are able to give up their energy to the neon, and, since the pressure of neon is 10,000 times that of sodium, it is extremely improbable that a sodium atom will be excited or ionized by a primary

electron before the latter has lost energy to a neon atom. On the other hand, the secondary electrons are unable to cause any excitation of neon, and although they may have collided several thousand times with neon atoms before striking a sodium atom, they will still be able to excite the latter. *Thus, in a cathodic sodium lamp the generation of light is produced mainly by the secondary electrons and the light output determined by the number and energy of these electrons.*"

Electron Temperature

Owing to their low velocity as compared with both primaries and secondaries, the ultimate electrons constitute the largest fraction of the electrons in the plasma. As shown by the investigation of I. Langmuir and H. Mott-Smith[15, 25] these electrons possess a Maxwellian distribution of velocities which is defined in terms of an "electron temperature" T_e, and the Maxwell-Boltzmann equation

$$n = n_e \epsilon^{-Ve/kT_e}. \tag{16a}$$

In this equation n_e is the concentration of electrons in the plasma and n/n_e is that fraction which has an energy in excess of V electron volts. Since $e/k = 11{,}600$ deg. K per volt, the last equation is usually written in the form

$$n = n_e \epsilon^{-11,600V/T_e}. \tag{16b}$$

By measuring the current to a fine wire (or small disk) inserted in the plasma, as a function of the potential of the probe with respect to either the cathode or anode, it is possible to determine both I_e the random current, and T_e for these ultimate electrons.

The positive ions do not possess a Maxwellian distribution, but actual observations in positive column discharges have led to the relation

$$I_e/I_p = (m_p/2m_e)^{\frac{1}{2}} \tag{17}$$

where I_e and I_p represent the random currents of electrons and positive ions, respectively. Thus, for a discharge in neon, the value of the right-hand expression is 136.1, and the fact that the random current densities in the plasma are so different leads to the formation of sheaths on the walls and other insulated surfaces. Since in the steady state the rates at which negative and positive charges reach any insulated surface must be the same, the latter must become charged to such a negative value that, for instance in neon, 135.1 electrons are repelled for every one that actually reaches the surface. The walls thus become covered with a positive ion sheath, and the potential drop in this sheath (V_s) can be calculated, if the random electron current to the surface (I_w) and I_e are known, by means of the equation

$$I_w = I_e \epsilon^{-11,600V_s/T_e}, \tag{18}$$

which follows from Eq. (16b).

For instance, in a cathodic discharge in neon at 1 mm, it was found that $T_e = 5500°\text{K}$, and consequently $V_s = 2.33$ volts. The values of T_e observed vary with V_c, the nature of the gas, and other factors. In all cases T_e is *considerably greater* than the temperature of the gas molecules (T_g), which obviously is the same as that of the glass walls. In general, it may be stated that T_e decreases as the pressure is increased from, for instance, 1 mm to 10 mm, but in any cathodic type of discharge T_e is always greater than T_g.

Light Output in Cathodic Discharge Lamp

Summarizing the discussion in the previous sections it follows that in a cathodic discharge the extent of the light region is governed by the distance which the electrons traverse before they become ultimate electrons. The light output is therefore a function of both gas pressure and of V_c, and the latter is in turn governed by the thermionic emissivity of the cathode. As has been emphasized already, the function of the ions is merely that of eliminating space charge. In consequence, the voltage drop in the arc adjusts itself to such a value for any given arc current that both a sufficiently strong field will exist at the cathode to provide the necessary electron emission and to enable the electrons to acquire sufficient energy to produce the necessary amount of ionization.

In a cathodic discharge in neon-sodium the pressure of neon is about 1 mm, and under conditions of optimum light output the pressure of sodium vapor is about 0.001 mm. In a previous section the processes which occur in this discharge have been discussed. The value of V_c actually observed in such a discharge is about 18 or 19 volts when optimum light output is obtained, and it is only when the vapor pressure of sodium increases to values above 0.002 mm that V_c

decreases to about 8 volts and at the same time the neon lines disappear. The fact that V_c in a neon sodium discharge has a value which is approximately equal to $V_m+2.5$ and is lower than the ionization potential of neon by 2.5 to 3.5 volts shows the important role played by metastable neon atoms. The electrons acquire sufficient energy in the cathode sheath to excite neon atoms to the metastable state and the residual 2 to 2.5 volts is then used either to excite these metastable atoms to higher states or to excite sodium atoms to the resonance state. Actually, there is an even greater probability that an electron accelerated through the cathode sheath will ionize a metastable atom. Since the energy required for this purpose is about 5 volts, the secondary electron which results from such an impact still retains $19-5=14$ volts kinetic energy and may therefore ionize at least two other metastable neon atoms.

From this point of view a discharge in neon at 1 mm pressure may be regarded as a discharge with a cathode drop of 18 or 19 volts in a gas which has an ionization potential of 5 volts and a first excitation potential of 2 volts.

On this basis it is possible to show[47] that as a first approximation the light output should be proportional to the current, and actually it has been observed by Found[44] that for a large range of values of arc current, the light output is 1000 lumens per ampere. "This corresponds," as Found points out, "to the generation of one light quantum per primary electron." At higher currents the ratio decreases and when the discharge is all sodium, the light output is only about 500 lumens per ampere.

Positive Column Discharge Lamps*

In a cathodic type of discharge, the electrons acquire a high kinetic energy in the cathode sheath and then lose this energy in excitation and ionization of atoms. Thus the kinetic energy decreases with increase in distance from cathode, and finally when the electrons have reached the stage in which their kinetic energy is no longer adequate for excitation (ultimate electrons) the light generation also disappears.

The fact that the light generation is uniform throughout the length of the positive column shows that the electrons must acquire energy for excitation and ionization from some other source than the cathode fall. This energy is supplied, obviously, by the energy input into the column, that is, Gi_A watts per unit length, where G is the voltage gradient and i_A the arc current. The magnitude of G varies with current density and pressure of gas.

According to the theoretical considerations developed in 1924 by W. Schottky,[5, 6, 7] the gradient in a positive column discharge should vary approximately inversely as tube diameter, when current and pressure of gas are maintained constant. The larger the diameter, the smaller the relative loss of ions and electrons by diffusion to the walls, and hence the smaller the energy input to compensate for this loss of charged particles. The values of G observed by C. G. Found and J. D. Forney[18] for discharges in neon using different diameters of tube were found to be in satisfactory agreement with Schottky's conclusion.

Owing to the fact that the gradient in a positive column is constant, the concentrations of electrons and positive ions in the column must be approximately equal. Since the ions and electrons are constantly diffusing to the walls, there must be some mechanism by which fresh ions are generated, and the only method available is the impact of high speed ultimate electrons. According to Eq. (16b) the fraction of the electrons which have an energy in excess of a given value of V depends upon the value of T_e.

Thus for a positive column discharge in neon under operating conditions a value of $T_e=40{,}000$ would correspond to a value for $V=16.5$ of $n/n_e=0.009$. That is, approximately one electron in 100 would have a kinetic energy equal to or in excess of the value of V_m. Similarly, in a discharge in mercury vapor at a pressure of 0.00533 mm, the value of T_e observed under certain conditions was 19,900°K. The fraction of the electrons with an energy in excess of 10.4 volts (V_i for mercury) would be 0.003. Thus, the electron temperature is the most important factor in maintaining the ionization and excitation in a positive column discharge, and consequently it is the most important factor from the point of view of light output.

* See references 29a, 29b, 31, 35, 41a, 41b, 49, 50, 51, 56 and 68.

Light Output in Positive Column Discharge

In order to obtain considerable light output with appreciable intrinsic brilliancy of source, the positive column is more advantageous than the cathodic type of discharge. Thus, in the case of low pressure mercury vapor and sodium neon lamps it has been found that from the point of view of both lumen output and efficiency the best results are obtained with the positive column type of lamp.

While the mercury vapor lamp of this type has been a familiar form of illumination for many years, it is only within the past few years that it has been found possible to develop a commercial type of sodium vapor positive column lamp for use on standard alternating current circuits. Such lamps have been developed by the Osram Company in Germany, and by the Philips' Lamp Company in Holland.† A lamp emitting approximately 10,000 lumens at an input of about 190 watts has been described by G. R. Fonda and A. H. Young.[45] Fig. 10[46b] shows the design of this lamp and connections for series-circuit operation. The electrodes are oxide-coated tungsten spirals enclosed by elliptically shaped anodes, with a distance of about 25 cm between the latter. The pressure of neon used varies from 1 to 3 mm, and under operating conditions (6.6 amp. constant current and a drop of 27–30 volts) the pressure of sodium vapor is approximately 0.001 mm.

The glass is covered internally with a sodium resistant glaze and the lamp itself is enclosed in a transparent Dewar flask in order to maintain the pressure of sodium vapor at the optimum value (which corresponds to a temperature in the neighborhood of 230°C).

Now let us consider the phenomena of light production in such a lamp. The electrons in a positive column discharge are distributed throughout the whole volume. Therefore, the excitation, ionization and light production are each uniformly distributed along the column. In the case of the positive column discharge in sodium and neon, the neon plays the same predominating role as in the cathodic discharge lamp. As shown by the work of H. Kopferman and R. Ladenburg[10, 13] the concentration of

† European types of sodium vapor lamps are described in references 29a, 29b, 33, 48, 49 and 52.

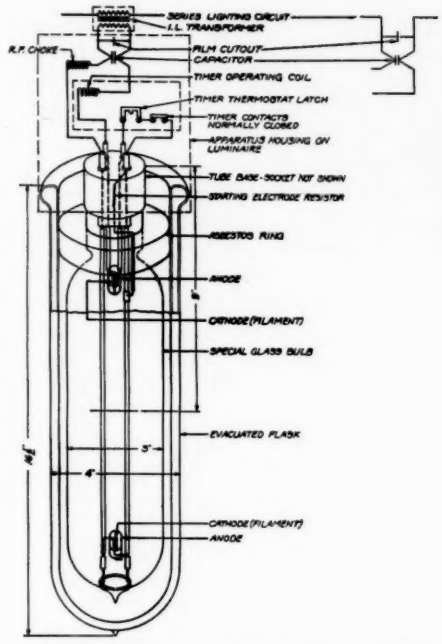

Fig. 10. 10,000 lumen a.c. sodium lamp, showing connections for operation of cathodes in series with arc.

metastable neon atoms in a positive column discharge is quite high and comparable with the values of n_e. It is therefore extremely probable that the ions in such a discharge are produced by cumulative action as in the cathodic discharge.

A very complete set of data on the gradient, electron temperature and electron concentration in a positive column discharge in sodium and sodium plus neon, in a tube 3.6 cm in diameter, has been published by M. J. Druyvesteyn and

Table IV. *Data for positive column discharge in sodium and sodium plus neon tube diameter = 3.6 cm.*

							E_R	E_W
t°C	p(Na) mm	p(Ne) mm	Arc amp.	G volts/cm	T_e	$n_e \cdot 10^{-10}$	Percentage of Total	
255	0.0021	0	0.2	0.432	30,950	1.01	92.2	13.3
		0	1.0	0.398	19,200	4.55	93.7	13.8
			1.0	0.504	9,100	39.9	88.8	12.5
		3.0	1.0	0.461	8,050	67.0	88.3	10.3
273	0.0044	0	0.2	0.748	22,750	1.25	91.4	6.0
		0	1.0	0.555	12,600	8.64	91.7	8.0
		1.1	1.0	0.481	8,050	39.9	90.5	9.9
		3.2	1.0	0.440	7,600	77.0	87.5	9.4
287	0.008	0	1.0	0.668	9,600	14.8	92.3	6.4
		1.07	1.0	0.517	8,050	39.8	92.0	8.6
		3.1	1.0	0.443	7,100	75.0	90.5	9.6
		5.0	1.0	0.440	6,600	97.0	87.4	8.0

N. Warmoltz.[27] Some of this data is shown in Table IV. The measurements were taken with the tube connected to a sodium reservoir maintained at the temperature indicated in the first column. Since the tube itself was at 330 deg. C, there was no condensation of sodium along the walls of the tube. While the second column gives the vapor pressure at the corresponding temperature, the actual pressure in the tube varied with distance from cathode owing to migration of sodium ions. The third column gives the pressure of neon as measured by a gauge at room temperature. The values of G, T_e and n_e were determined by probe measurements. The last two columns give data which will be considered in a subsequent section in connection with energy balance in a positive column.

It will be observed that, as in the case of measurements with mercury vapor discharges, T_e and G decrease with increases in pressure, while n_e increases. Assuming, according to Schottky's deductions, that G varies inversely as tube diameter d, the relative values of Gd and T_e for the same vapor pressure are found to be higher in mercury than in sodium. This is what would be expected in view of the relative values of V_i (and V_r). The fact that the voltage gradient is increased by addition of neon when the sodium pressure is low and decreased by addition of neon when the sodium pressure is higher, shows that at the low pressures of sodium the ions are supplied by neon, while at higher pressures of sodium the ions are obtained from the latter.

The data obtained by Druyvesteyn and Warmoltz are in agreement with observations recorded by G. R. Fonda and A. H. Young[42] on the 10,000 lumen a.c. lamp described previously. In these experiments the arc current was maintained at 4 amp., and the neon pressure was 1.5 mm. On varying the temperature of the lamp, thus varying the vapor pressure of sodium, the following relation was obtained for T_e as a function of vapor pressure of sodium (p in mm of mercury):

$$\log T_e = 3.486 - 0.193 \log p.$$

That is, T_e decreased with increase in p. It was also observed that T_e decreased and n_e increased with increase in arc current, a result which is also in agreement with the data given in Table IV.

From the data given in the latter it is possible to make an approximate calculation of the relative intensities of D line radiation which might be expected for two different current values. Thus, for a pressure of 1.1 mm of neon and 0.0021 mm of sodium, the observed values of T_e show that the actual concentration of electrons with kinetic energy in excess of 2.10 volts, that is,

$$n = n_e \epsilon^{-2.10 \times 11,600/T_e}$$

are as follows:

at 0.2 amp., $n = 1.45 \times 10^{-10}$
at 1.0 amp., $n = 2.765 \times 10^{-10}$.

Thus, while the ratio of arc currents is 5 : 1, the ratio of the electron concentrations capable of exciting sodium atoms is 2.4 : 1. Consequently, the total light output should increase 2.4-fold, and since the gradient has decreased to 1/2, the luminous efficiency should be practically the same. The last column in Table IV shows that the total energy radiated (E_R) which includes both visible and infrared, was approximately constant. While this does not give any information about the percentage in the visible, it is probably justifiable to assume, in view of other results in the same paper on the distribution of E_R between visible and infrared, that the fraction in the visible decreases with increase in arc current.

This inference is in agreement with the photometric measurements of Fonda and Young which show that the light output per ampere decreases with increase in arc current. Thus, at a pressure of sodium corresponding to 200 deg. C (with 1.5 mm neon present) the relative light output per ampere decreased from 74 to 42 for a change in arc current from 1 to 5 amp. At very low current densities, the relative lumen output per ampere increased considerably, so that at 0.075 amp. and 265 deg. C, an efficiency of 315 lumens per watt was obtained, which represents 66 percent of L_0, the optimum luminous efficiency. A similar result has also been obtained by M. Pirani[30] with sodium vapor discharges in which heat was applied from an external source to evaporate the sodium.

Energy Balance in a Positive Column Discharge

In their very comprehensive paper on the "Theory of the Arc Plasma,"[19] L. Tonks and I. Langmuir have discussed the energy balance in a positive column. The power input per unit length is Gi_A, where i_A is the arc current. This power is distributed as follows (see discussion by C. G. Found):[44]

(a) Elastic collisions between electrons and gas atoms

The fraction of the energy lost by an electron at each collision of this type is $2m/M$, where m is the mass of the electron, and M that of the atom. For helium this ratio has the value 2.72×10^{-4}, and is evidently less than this for all other gases. Except in the case of high pressures, the energy (per unit length of column) lost in this manner, known as the volume energy E_v, must be negligibly small.

(b) Production of positive ions

At low pressures where recombination between ions and electrons in the plasma is extremely improbable, the rate of generation of ions per unit length of discharge column must be equal to the rate at which ions flow to the wall, per unit length of tube, and are neutralized there by an equal current of electrons. As mentioned in a previous section, there exists on the walls of any discharge tube a sheath in which there is an electron space charge and a drop V_s. If I_p denotes the random positive ion current density in the discharge, then the positive ion current flowing to the walls per unit length is

$$I_w = I_p \cdot 2\pi a, \tag{19}$$

where a is the radius of tube. The energy transmitted to the walls by the ions because of the sheath drop is $V_s \cdot I_w$, and the energy carried to unit length of the walls by electrons is

$$I_w(2k/e)T_e = I_w(2T_e/11{,}600).$$

Furthermore, the energy evolved by recombination at the walls is $I_w \cdot V_i$. Hence the total energy delivered to the walls (per unit length) because of the flow of ions and electrons is

$$E_w = I_w(V_i + V_s + 2T_e/11{,}600). \tag{20}$$

(c) Production of excited atoms

The energy thus utilized is restored in the form of radiation. Part of this energy (E_T) is transmitted through the walls as visible, infrared and ultraviolet radiations. This may be measured by means of a thermopile. The rest of the energy (E_A) is absorbed by the walls. This is either reemitted to the external environment by radiation and conduction or utilized in increasing the temperature of the gas in the tube. The total energy resulting from production of excited atoms is therefore

$$E_R = E_T + E_A. \tag{21}$$

Of the transmitted radiation a certain fraction is in the visible range. Let L denote the lumens per unit length, and $\bar{V}_\lambda$ the mean visibility factor. Then the energy converted into light is

$$E_L = L/(621\,\bar{V}_\lambda), \tag{22}$$

where E_L is usually less than E_T.

The energy balance equation is thus of the form

$$\begin{aligned} Gi_A &= E_v + E_w + E_R \\ &= E_v + E_w + E_T + E_A. \end{aligned} \tag{23}$$

The total energy absorbed by the walls is

$$E_{wA} = E_w + E_A, \tag{24}$$

and this may be determined directly by measuring the energy emitted per unit length immediately after the discharge is stopped.

The energy balance in a discharge has been the subject of a number of investigations. T. J. Killian[20] worked with a discharge in mercury vapor at low pressures. He found that as the pressure of mercury vapor was increased, the value of T_e decreased from 38,000 to 19,900°K, and E_w decreased from 48 to 14 percent of the total input. He did not, however, measure the energy radiated.

The measurements of W. Pupp[21] and K. Sommermeyer[23] are difficult to interpret, since the values which they obtained for E_v, the volume energy, appear to be abnormally high. On the other hand, the results obtained by F. L. Mohler[24] on a positive column discharge in caesium vapor are in very satisfactory agreement with Eq. (23). He found that the first doublet of the principal series at 8521 and 8944A

(which corresponds to the two D lines of sodium) contributes most of the radiation. The vapor pressure ranged from 0.001 to 0.3 mm and the tube used had a diameter of 1.8 cm. With currents of 1 amp. or less and pressures less than 0.03 mm the power input was nearly all accounted for in terms of E_R and E_w, with the latter gradually increasing in relative amount until at 4 amp., E_w was about twice E_R. At higher pressures there was an excess of power input which could not be accounted for but was probably due to volume losses (E_v) and infrared radiation. "It is reassuring," he states, "to find that over a considerable range the power loss is predominantly radiation of the resonance lines and recombination on the walls. It suggests that an approximate theory can be developed which considers production of ions and of the first excited state exclusively and that other phenomena can be treated independently."

His observations, as Mohler points out, are in agreement with those on the sodium positive column lamp. In the latter, under normal operating conditions the energy radiated in D lines is about 20 percent of the power input in the positive column, but if external heating is used, a radiation efficiency as high as 70 percent may be obtained at low current densities as mentioned in a previous section.

The energy balance in sodium vapor and sodium vapor neon discharges was also investigated by Druyvesteyn and Warmoltz. In Table IV the last two columns give their results on the percentages of the total power input utilized in radiation E_R and wall energy E_w (E_v was negligible, as expected). It will be observed that the total adds up to over 100 percent in some cases and less than 100 percent in others. One conclusion however is evident—that about 90 percent of the total energy input was utilized in these experiments in excitation of atoms, and the other 10 percent in recombination at the walls.

Investigations on the energy distribution in the spectrum of sodium show that the radiation emitted by this vapor consists mainly of the D lines 5890 and 5896, and the three infrared lines λ8200, λ11,400 and λ22,000. (See Fig. 5.) The other lines in the visible part of the spectrum constitute altogether only about 2 percent of the total light. Druyvesteyn and Warmoltz do not give data on the manner in which the energy radiated is distributed among the different infrared lines and the D lines; but in some other cases they found that the infrared radiation increases from 12 percent to 14 percent at the lowest current densities to 50 percent at the highest current densities. At high current densities the concentration of excited sodium atoms in the $3P$ state is so large that excitation to still higher levels becomes extremely probable.

At higher pressures of neon and especially at higher current densities, Druyvesteyn and Warmoltz observed a residual input energy in excess of E_R+E_w which they found to be of the same order of magnitude as that calculated for loss by elastic collision (E_v). These measurements thus show that Eq. (23) gives a fairly satisfactory interpretation of the processes occurring in positive column discharges at low pressures.

The problem of energy utilization in positive column discharges has also been discussed along

FIG. 11. High intensity 400-watt mercury vapor lamp.

more general lines by M. Pirani and his associates in a number of publications.[34, 36, 53]

In this connection it is of interest to calculate the relative concentrations of excited atoms in the $3P$ state in a lamp such as the 10,000 lumen a.c. lamp. Since the temperature of the bulb is about 220 deg. C, the pressure of sodium is about 0.0001 mm, and the concentration of sodium atoms n_{Na} is 10^{13} per cubic centimeter. As shown by Ladenburg the concentration of atoms in the different excited states may be calculated by means of the Boltzmann distribution law if the value of the temperature used is that corresponding to T_e. According to measurements by G. R. Fonda,[42] the value of T_e in the positive column part of the a.c. sodium plus neon lamp is about 8000 deg. K (equivalent to 0.7 volt). Hence, the concentration of atoms in the $3P$ state n_a is given in terms of n_{Na} by the relation

$$n_a/n_{Na}=3\cdot\epsilon^{-2.10/0.7}=0.15,$$

and therefore $n_a=1.5\times10^{12}/\text{cm}^3$.

This seems to be a reasonable value in view of the measurements on absorption of resonance radiation and on light efficiency.

Summarizing these results it is seen that in the case of a positive column discharge in a vapor such as mercury or sodium, a certain amount of energy must be used to maintain an optimum vapor pressure with the arc current used. This energy is provided by recombination of electrons and ions on the walls. Other losses arise from the emission of ultraviolet and infrared radiation.

By use of fluorescent materials, as mentioned in a subsequent section, it is possible to convert some or all of the ultraviolet radiation into visible light. This procedure has, however, only limited application. The losses arising from positive ion currents to the walls and from emission of infrared radiation, as well as electrode losses are inherent in any discharge. While some of these losses may be reduced by suitable design of tube and choice of optimum operating conditions (as shown by the investigations of G. R. Fonda and A. H. Young in the case of sodium vapor neon discharges)[45] it is necessary, in all cases, to effect a compromise between efficiency and total light output. For instance, it might be possible to obtain higher efficiencies in a sodium vapor neon lamp by operating at much lower current densities, but under these circumstances the dimensions of a lamp which should emit sufficient lumens for practical purposes, would become impractically large. However, in these and similar discharge lamps it is probable that further investigations will lead to designs in which high lumen output will be possible with even higher efficiencies than those obtained hitherto.

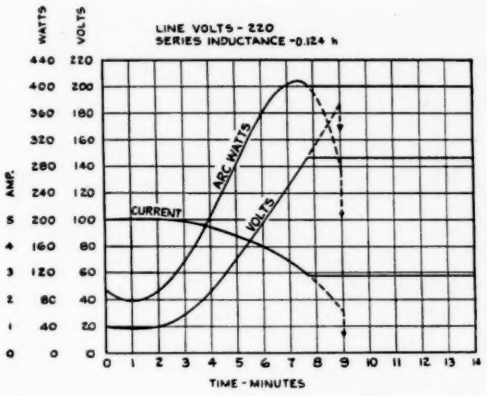

FIG. 12. Electrical characteristics of 400-watt mercury vapor arc between time of starting and complete vaporization of mercury.

HIGH PRESSURE POSITIVE COLUMN DISCHARGE LAMPS

While the discharge lamps discussed in the previous sections are all of the low pressure type, there has been a rapid development in recent years of lamps in which the discharge occurs in mercury vapor at a pressure of one atmosphere or higher. The earliest form of such a discharge was the quartz tubular lamp which has been used mainly as a source of ultraviolet. In this case the arc is formed by breaking a mercury column, and as the vapor pressure is increased, due to the high energy input, the light output as well as the efficiency of light production are also increased.

By the application of thermionic cathodes it has been found possible to develop designs in which these advantages of operating at higher pressures are obtained with greater convenience. In all these forms a gas, such as neon or argon at a pressure of a few centimeters of mercury, is used to initiate the discharge between the

TABLE V. *Degree of ionization of mercury at a series of temperatures and two different pressures.*

T	α AT $P=1$ ATM.	$P=100$ ATM.
5000	1.38×10^{-4}	1.38×10^{-5}
5500	4.65×10^{-4}	4.65×10^{-5}
6000	1.29×10^{-3}	1.29×10^{-4}
6500	3.09×10^{-3}	3.09×10^{-4}
7000	6.59×10^{-3}	6.59×10^{-4}
8000	2.28×10^{-2}	2.28×10^{-3}
9000	7.67×10^{-2}	7.67×10^{-3}

cathodes which are thereby raised to a temperature at which they act as thermionic sources. Owing to the high energy input the mercury becomes vaporized, the pressure increases to one atmosphere or even higher, depending upon the design of lamp and operating conditions, and the spectrum exhibits only those lines which are characteristic of mercury along with a certain amount of continuous radiation.

Measurements of the relative intensities of the lines and of the energy distribution in the spectrum made on discharges in quartz tubes at different pressures* show that while the intensity of the resonance line ($\lambda=2537$A) is very high at low currents and low pressures, this line is practically eliminated (owing to absorption) in the discharge at 1 atmosphere and higher pressures. At the higher pressures the intensity of the lines $\lambda=3650/3663$, $\lambda=5461$, and $\lambda=5769/5790$ are increased. In a very recent publication by W. Ellenbaas[70] it is shown that at higher pressures the spectral lines are broadened more and more with increase in pressure and at higher current densities the continuous spectrum is enhanced. Also the fraction of the total energy radiated in the form of near ultraviolet, visible, and infrared, increases with increase in pressure, and this accounts for the observed increase in light efficiency (see subsequent remarks).

The various designs of the high pressure discharge lamp which have been developed may be divided into two groups: (1) Those operating at one atmosphere and utilizing glass envelopes, and (2) Those operating at higher pressures and requiring the use of quartz envelopes.

TABLE VI.

d	m	G	W	i	T	p	L	L_a
20	3.1	7.6	40	5.26	6284	1.0	1,650	41
3	30.0	606.0	600	0.99	6794	300.0	30,000	50
20	10.0	16.1	40	2.48	5732	2.8	1,830	45.7

* See references 38, 40, 50, 53, 57a, 66 and 67.

Fig. 11 shows a diagram of the one atmosphere lamp developed by the General Electric Co., Ltd., Wembley, England, and described by J. W. Ryde.[39] The inner glass tube which carries the arc is enclosed in a heat insulating jacket. The wire along the outside of the discharge tube is for the purpose of easier starting.

Similar types of lamps developed in this country have been described by J. W. Marden, N. C. Beese and G. Meister[57a, 57b] and by J. A. St. Louis.[54] The following data are taken from the publication by the latter.

The lamp is made in both 400-watt and 250-watt units and operates on a 220-volt a.c. circuit with series inductance. Argon is used as starting gas and a *limited* amount of liquid mercury is inserted in the lamp initially. Fig. 12 shows the electrical characteristics of the 400-watt unit between time of starting and complete vaporization of the mercury. It will be observed that the initial volts and arc watts are low, but that after a slight decrease, both the voltage drop in the arc and power input increase rapidly. "During this period of rapidly increasing pressure," as St. Louis observes, "the arc constricts. The wattage passes through a maximum but the voltage increases with time as long as any liquid mercury remains in the tube. After about seven minutes all the mercury is vaporized and the electrical characteristics are thereafter constant. If the mercury were not limited in amount, then the course of these characteristic curves would continue as indicated by the dotted lines. It should be emphasized that the shape of these characteristic curves is influenced by the value of the series inductance, by the value of the line voltage, and by the design details of the arc tube."

While it is possible to design the lamp so that equilibrium is attained with liquid mercury at a temperature corresponding to any desired mercury vapor pressure, the use of a limited amount of mercury has many practical advantages, not the least of these being the fact that under these conditions the lamp is not nearly so sensitive to fluctuations in either line voltage or ambient temperature.

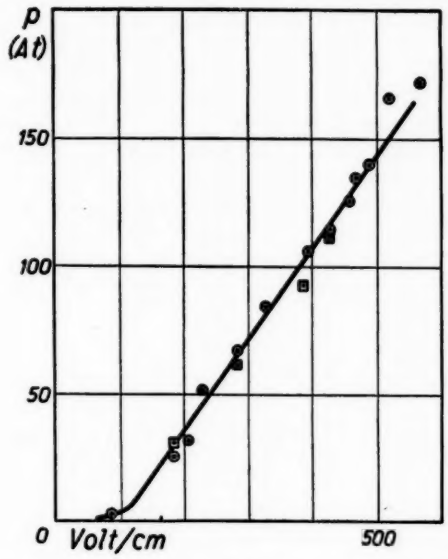

FIG. 13. Pressure in very high pressure mercury vapor lamps as function of gradient.

Under operating conditions the temperature of the inner glass wall is about 350°C, the pressure of mercury one atmosphere, and the initial efficiency is 40 lumens per watt. This efficiency decreases after 1500 hours to about 33 lumens per watt.

One of the most interesting of the recent developments in the field of illumination is the quartz capillary lamp developed by C. Bol[68] of the Philips Lamp Co., Eindhoven, Holland. The air-cooled form which operates at 230 volts with a power input of about 85 watts consists of a quartz capillary 4 mm in diameter, with a total distance of 18 mm between the oxide-coated tungsten electrodes. A small drop of mercury is inserted and argon is used as a starting gas. The lamp is operated on a high reactance transformer which has a maximum open circuit voltage of about 450 volts. The pressure of mercury vapor attained in operation depends for a given size of capillary upon the gradient and arc current, but is usually between 5 and 25 atmospheres.

By cooling the walls of the quartz capillary in a rapid stream of water, the wattage input may be increased to over fivefold and while this increases the efficiency from approximately 40 lumens/watt obtained in the air-cooled to 60 lumens/watt or slightly higher, the intrinsic brilliancy and lumen output are increased manyfold. In fact, during the present year W. Ellenbaas[65] has reported that by increasing the power input in the water-cooled lamp to 1400 watts/cm in a 1 mm diameter tube, a brilliancy of 180,000 candles/cm^2 has been attained. This is greater than that of the sun, as observed from the surface of the earth, which is 165,000 candles/cm^2.

A very comprehensive study of the characteristics of high pressure mercury vapor discharges has been made by W. Ellenbaas.[61, 62, 63, 64] Since a summary of these investigations has been published by G. Heller,[69] it is only necessary, in the present connection, to emphasize briefly some of the more significant aspects of this work.

The most important difference between the discharge in high pressures (1 atmosphere or higher) and that in much lower pressures is that while in the latter, the electron temperature T_e is considerably greater than the gas temperature T_g, these two magnitudes are equal in a high pressure discharge. That is, there is *thermal equilibrium* in the sense that the *temperature of the gas determines the energy distribution of atoms, ions and electrons*, and consequently also, *the degree of ionization, the conductivity, and power input for a given current.*

Let α denote the degree of ionization, and P the total pressure. Then we can calculate α for

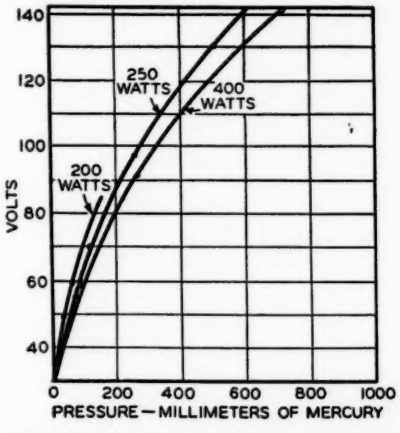

FIG. 14. Relationship between pressure and voltage for a high intensity mercury-arc lamp.

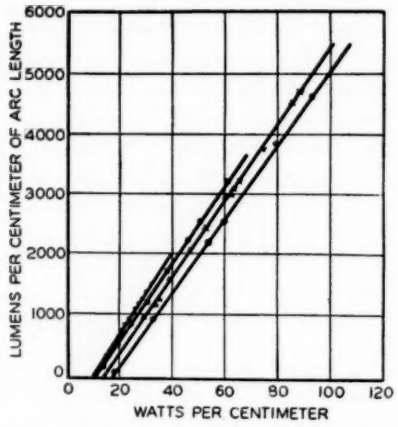

FIG. 15. Relationship between wattage and light output for high intensity mercury-arc lamps having arc lengths of 100, 40, 15 and 7 millimeters (left to right).

a given value of T and P by means of Saha's equation[11]

$$\log \frac{\alpha^2 P}{1-\alpha^2} = -\frac{V_i e}{2 \cdot 30 kT} + \frac{5}{2} \log T + \log I, \quad (25a)$$

where $I = (2\pi\mu)^{3/2} k^{5/2} h^{-3}$,

μ = mass of electron,

and logarithms to base 10 are used.

In the case of mercury, $V_i = 10.39$ ev, and consequently Eq. (25a) becomes

$$\log \frac{\alpha^2 P}{1-\alpha^2} = -\frac{52{,}340}{T} + \frac{5}{2} \log T - 6.50, \quad (25b)$$

where P is expressed in atmospheres.

The temperature in a high pressure discharge was calculated by observing the watts input per unit length (W) required to maintain the pressure on the walls at one atmosphere with a given mass of mercury per unit length (m). Assuming an approximately parabolic distribution of temperature from the axis of the tube to the walls, it was found that for a tube 20 mm in diameter with an input energy of 43.8 watts/cm length, the value of T at the center (for 1 atmosphere pressure) is about 6000°K. The value of the wall temperature is in all cases about 1100°K. On the basis of the energy balance equation and the similarity relations, which are discussed in the following paragraphs, Ellenbaas has deduced the relation

$$T = 6025(W/(8.5+5.75m))^{0.1}, \quad (26)$$

which shows that T increases with W and decreases with increase in m. This leads to values of T ranging, under operating conditions, from below 5500°K to over 8000°K.

Values of α calculated by means of Eq. (25b) for such a range of temperatures and at two widely different pressures are shown in Table V.

The arc current i_A is given in terms of the electron concentration (n) by the relation

$$\begin{aligned} i_A &= nev, \\ &= nekG, \end{aligned} \quad (27)$$

where v is the velocity of the electrons under the action of the voltage gradient G, and k is a constant which may be calculated by means of a formula first derived by Langevin (1905) on the basis of kinetic theory considerations.[11]

Since the concentration of electrons is equal to that of the positive ions and this is given by the value of αP, it follows that from a calculation of the latter and a determination of G it should be possible to derive values of i_A. As shown by Ellenbaas the agreement between the calculated and observed values of i_A is very satisfactory.

From a consideration of the energy balance in a high pressure discharge W. Ellenbaas has also deduced some very significant relations which apply to such discharges independently of variations in the different independent parameters. He defines high pressure discharges as similar when the *temperatures at homologous points in the discharge are the same*, and shows that different discharges will be similar if the following relations apply:

$$W/(A+Bm) = \text{const.}; \quad (28)$$

and $$(G^2 d^3 m^{-1})/(A+Bm) = \text{const.}, \quad (29)$$

where d is the diameter of tube, and A and B are constants. The quantities A and Bm are interpreted as energy losses due to conduction

TABLE VII.

	TEMPERATURE K	I	E	n	$\alpha = n/N$	V_i
Cu electrodes	4050	10	16.5	0.4×10^{14}	0.2×10^{-4}	9.5
Cored C projection arc	5500	50	10	1.6×10^{14}	1.2×10^{-4}	11.7
NaCl cored C	4740	85	6	7.0×10^{14}	4.5×10^{-4}	8.7
W electrodes	5950	20	22	0.2×10^{14}	0.16×10^{-4}	14.7

and radiation, respectively. The last equation may be expressed in the form

$$G^2d^3m^{-\frac{1}{2}} = (8.5+5.75m)10^4, \qquad (30)$$

where G = volts/cm,
d = diam. in mm,

and m = mgm Hg per cm length.

From Eq. (28) it follows that the efficiency of light production L_s is given by

$$L_s = (5.75\ m \cdot C)/(8.5+5.75m), \qquad (31)$$

where C is a constant. It follows that L_s increases with m for small values of this magnitude but tends to reach a constant value for very large values of m

To obtain high intrinsic brilliancy we must have W large as possible, that is m very large, and since this involves a high value of G it follows from Eq. (29) that d must be made very small.

Table VI shows values of T and G calculated by means of Eqs. (26) and (30), respectively, for three different sets of values of the parameters d and m. The values of W, L (lumens per cm length), L_s and p in the first two cases ($m = 3.1$ and $m = 606.0$) are those determined experimentally. Values of i, the arc current, were calculated from the values of G and W. Values of G and T were calculated for the case $d = 20$, $m = 10$, and assuming $W = 40$, the value of p was derived from the relation

$$G^2 = \text{const. } W \cdot p^{1/2}T^{-3/4} \cdot \epsilon^{V_i e/2kT}, \qquad (32)$$

which follows from Saha's equation.

The values of L_s and L for this case were calculated by means of Eq. (31) using the value $C = 52.5$ obtained by applying this equation to the second case in Table VI.

In the case of the water-cooled lamp mentioned previously in which the power input was 1400 watts per cm in a tube 1 mm diameter, the following values of the characteristics were obtained: $G = 805$ volts/cm; $P = 200$ atmospheres; and $T = 8900°$K.

For values of G in excess of 100 volts/cm, the pressure increases linearly with G, as shown in Fig. 13, taken from the paper by W. de Groot.[67] The points represent two alternating current discharges in a water-cooled tube 2 mm inside and 6 mm outside diameter. The current varied from 1 to 1.5 amperes. Fig. 14, taken from the paper by Marden, Beese and Meister,[57a] shows a similar plot for lower pressure lamps.

Ellenbaas and de Groot[66] have reported measurements on the total radiation from the super-high pressure discharge. In the case of the water-cooled lamp operating at 100 atmospheres pressure in a 2 mm quartz capillary, 1 cm long, the total power input was 460 watts and approximately 50 percent of this is radiated. For the air-cooled quartz lamp, operating at about 0.75 atmosphere pressure in a 23 mm diameter tube with an input of 26 watts per cm, the energy radiated was 27 percent and the efficiency of light production 39 lumens/watt. The latter value agrees well with that calculated from the energy radiated when the visibilities of the different lines are taken into account.

Fig. 15 (from the paper by Marden, Beese and Meister[57a]) shows a plot of the light output as a function of the watts/cm for the lower range of power input values. Undoubtedly, the higher efficiency of the very high pressure discharge is due to the cumulative excitation of metastable mercury atoms. In the case of the latter the luminous efficiency increases approximately linearly with the power input as the latter is increased from 10 to about 40 watts per cm. At 40 watts/cm the efficiency is about 39 lumens/watt, and as the power input is increased to 100 watts/cm, the efficiency increases to 60 lumens/watt.

In this connection it is of interest to mention the observations made by C. G. Suits[58, 59, 60] on the temperatures in different kinds of arcs in air. The temperature was determined by measuring the velocity propagation of sound in the arc stream.

Some of the results obtained are shown in Table VII. From the values of the voltage gradient (G) and current density (I) in the arc, the electron concentrations (n) were calculated by means of Eq. (27).

From the values of n thus calculated it is possible by application of Eq. (25a) to calculate the corresponding values of the ionization potential. Table VII gives values of n obtained from the arc characteristics and corresponding values of α, the fraction of the atoms ionized.

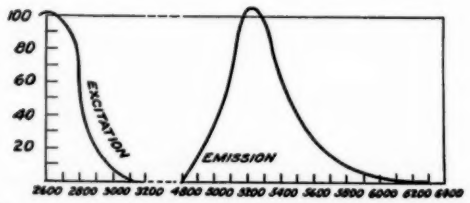

FIG. 16. Excitation and emission ranges of wave-lengths for activated zinc silicate.

The last column shows the calculated values of the ionization potential. As Suits points out there are present in the arc stream not only O_2 and N_2 but also electrode vapors. In the cases of the copper, cored carbon, and sodium arcs, the effect of the electrode vapor in decreasing V_i is noticeable, whereas in the case of the arc between tungsten electrodes the value of V_i is comparable with the observed values for molecular and atomic nitrogen which are 15.8 volts and 14.5 volts, respectively, and for atomic oxygen which is 13.6 volts. It should be observed that oxygen is practically completely dissociated at arc temperatures, and it is the energy supplied by recombination of atomic oxygen and nitrogen that accounts for the effectiveness of arc welding in air as compared with attempts to weld in an atmosphere of one of the rare gases.

TRANSFORMATION OF ULTRAVIOLET RADIATION INTO VISIBLE LIGHT*

That many materials fluoresce under the action of ultraviolet radiation is a fact which has been known for a long time, and quite a vast literature has accumulated describing both the methods of preparation of various "phosphors" and the relation between the emission spectra and the wave-length of exciting radiation. Some materials, like the sulphides of the elements of Group II in the periodic table (Lenard phosphors), respond to radiation in the range $\lambda = 3000$A to $\lambda = 4000$A, while others such as the silicates of zinc and cadmium and some of the tungstates and molybdates respond better to radiation in the neighborhood of $\lambda = 2537$A (the resonance line of Hg). In the case of the sulphides as well as the silicates the fluorescence is observed only if some "activator," such as Bi or Cu in the first case or Mn in the latter, is present.

* See list of references in bibliography.

Furthermore a large number of organic compounds, such as eosin, fluorescein and rhodamine *B*, have been found to exhibit fluorescence. The last named compound emits radiation in the orange-red under the influence of radiations in the near ultraviolet region and has therefore been suggested for use with the quartz capillary lamp described in a previous section. In this case the dye is painted on a reflector which surrounds the lamp.[83]

During recent years the problem of utilizing fluorescent materials to increase the efficiency of light sources has received considerable attention.[81] In Germany, M. Pirani and his associates in the laboratories of the Osram Company have made notable contributions in this field, and in this country Mr. G. Inman of the Incandescent Lamp Division of the General Electric Co., in Cleveland, has recently described a type of fluorescent lamp which is a highly efficient source of light.

A positive column discharge is passed through mercury vapor at low pressure (corresponding to the vapor pressure at slightly higher than room temperature). This constitutes a very efficient source of the mercury resonance radiation and by coating the inside of the discharge tube with a silicate or tungstate light in the visible range is obtained. The color emitted and the luminous efficiency vary with the composition and mode of preparation of the fluorescent material. Thus, by using a specially prepared zinc silicate, it is possible, according to Mr. Inman, to obtain light of a green color at an efficiency of 60 lumens/watt and even higher.

Fig. 16 shows observations made in this laboratory by Dr. G. R. Fonda on the excitation and emission spectrum of this silicate.† It will

TABLE VIII. *Efficiencies of Lenard phosphors.*

PHOSPHOR	λ_i	λ_e	EFFICIENCY	
			OBS.	CALC. FOR $f=1$
CaS+Bi	3660	4400	0.82	0.83
	4360	4400	0.97	0.99
ZnS+Cu	3660	5150	0.73	0.71
	4360	5150	0.84	0.85
CaS+Cu	3660	5250	0.64	0.70
	4360	5250	0.76	0.85

† These and other observations on a number of fluorescent materials will be discussed in a forthcoming paper. See also reference 56.

be observed that the two spectra are separated by quite a wide interval, which corresponds to about 1.4 electron volts. On the other hand, in the case of Lenard phosphors the maximum wave-length for excitation is adjacent to the minimum wave-length in the emission spectrum. From the point of view of an interpretation of the mechanism of fluorescence these observations should prove important. While our understanding of these phenomena is very indefinite at the present time, there is no doubt that the whole problem is intimately related to the presence of energy bands and localized levels in crystalline solids. Consequently, we may expect that further investigations along the same lines as those of Pohl, Gudden, and others (which have been discussed in the recent review by A. L. Hughes)[79] will be of material assistance in interpreting the phenomena of fluorescence and phosphorescence in general.

In the process of excitation and emission a photon of frequency ν_i is absorbed and probably transformed into a photon of frequency ν_e, so that under optimum conditions we would expect to obtain a *quantum efficiency* of unity for the *absorbed* radiation. This corresponds to an *energy efficiency* which is given by the ratio ν_e/ν_i. Table VIII shows the energy efficiencies for some of the Lenard phosphors.[82] The first column gives the composition of the material, the second and third columns the mean values of λ_i and λ_e, and the last two columns give the energy efficiency as observed and as calculated for a quantum efficiency (f) of unity.

Observations made by Dr. G. R. Fonda show that with the zinc and cadmium silicates, the values of f obtained range around 0.5.

From observations on the values of f it is possible to calculate the maximum values of L_s, the luminous efficiency, by means of the relation

$$L_s = \nu_e/\nu_i \times 621 \times V_\lambda = \lambda_i/\lambda_e \times 621 \times V_\lambda,$$

where V_λ refers to λ_e.

Thus for $\lambda_i = 4360$ and $\lambda_e = 5250$ ($V_\lambda = 0.78$) $L_s = 401$; while for $\lambda_i = 2537$ and $\lambda_e = 5250$, $L_s = 284$. On this basis the value of 70 lumens/watt actually observed represents a fairly high energy utilization ratio. In Table I, the value of L_0 was calculated on the same basis as for the gaseous discharges and incandescent lamps, that is, on the assumption that the emission is a primary phenomenon. It would seem more logical to use the value $L_0 = 284$ as an optimum value since actually the process is of a secondary nature.

Concluding Remarks

As stated at the beginning of this paper, no attempt has been made to discuss any of the technical applications of the various light sources. Nor has any mention been made of methods of photometry of colored light sources. References to these two aspects are given in the appended bibliography.

The future development of gaseous discharge lamps will depend upon a more intimate knowledge of the phenomena in these discharges. In spite of the vast amount of work during the past two decades, our understanding of some of the processes is still quite meager. Undoubtedly such investigations will lead not only to even higher efficiency light sources but also to devices which are more convenient for general use.

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Problems Concerning the Production of Cathode-Ray Tube Screens*

H. W. LEVERENZ
RCA Victor Division, RCA Manufacturing Co., Inc., Camden, New Jersey
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I. INTRODUCTION

THE scope of the present article is the description of some problems incidental to applying cathodoluminescent materials in cathode-ray (CR) tubes and Kinescopes (i.e., CR tubes with modulation as used in television) as these problems have been treated in the Electronic Research Laboratories at the Victor Division of the RCA Manufacturing Company, Inc.

Although much of that which follows is generalized, specific differences in theory and practice arise from the use of different cathodoluminescent materials (i.e., oxides or sulphides) and the use of different ways of viewing, projecting, or photographing the luminescent image (i.e., whether on the obverse or reverse side to that which is struck by the scanning electron beam).

Most of the described experimental procedures have been developed for producing oxide-type luminescent screens in CR tubes such as shown in Fig. 1. In this usual type of tube the image is viewed, or projected, from the side of the screen which is opposite the scanning beam. A major portion of this article will be devoted to the screening problems of this type of tube.

CR tubes in which the screen is viewed from the same side as it is scanned, such as sketched in Fig. 2, are the least complicated and most efficient types as far as image contrast and screen efficiency are concerned. However, such "direct-viewing" tubes have over-compensating disadvantages of geometry and the unfavorable psychological impression of looking at the image through a window.

Before proceeding with tube and screen types, we shall calculate the penetration distances of cathode rays into several luminescent materials.

II. CALCULATION OF CATHODE-RAY PENETRATION INTO SEVERAL IMPORTANT LUMINESCENT MATERIALS

H. Bethe[1] has developed a general formula for the penetration (p) of a corpuscular beam into matter:

* Read by invitation at the meeting of the Optical Society of America held at New York on October 30 and 31, 1936.

[1] Ann. d. Physik **5**, 325–401 (1930).

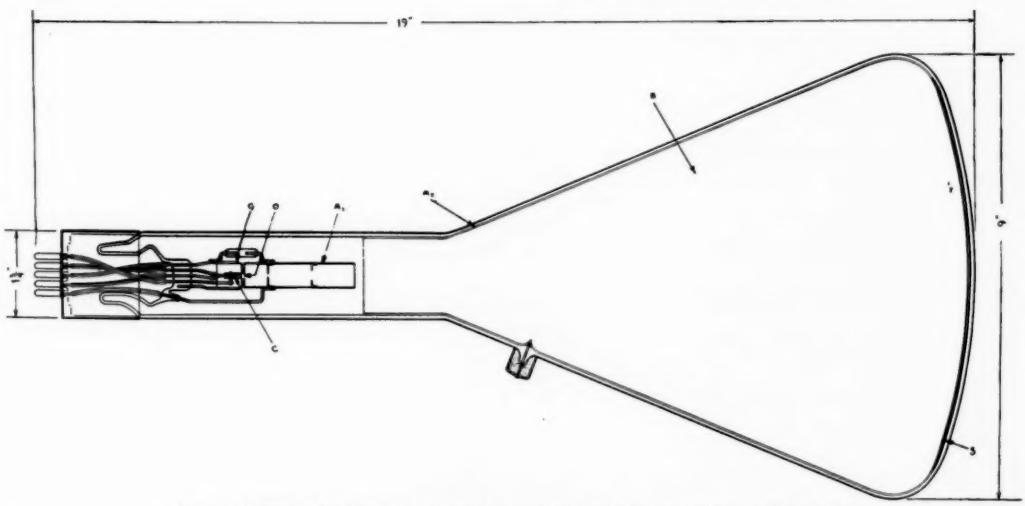

FIG. 1. Longitudinal section through a typical cathode-ray tube or Kinescope.

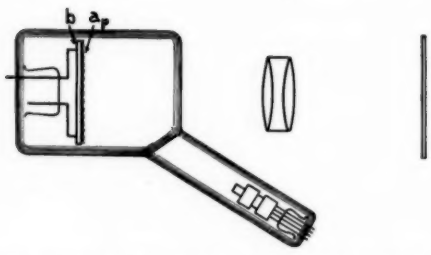

FIG. 2. Longitudinal section through a "direct viewing" or "front surface" type cathode-ray tube (Kinescope).

$$\frac{v_0^4 - v^4}{p} = \frac{16\pi e^4 z^2 N}{mM_1} \Sigma f_{nl} \ln \frac{4\overline{W}}{A_{nl}}, \qquad (1)$$

v_0 = initial velocity of particle,
v = velocity of particle after traversing the thickness p,
e = the electronic charge (4.774×10^{-10} E.S.U.),
z = number of charges carried per unit particle,
N = number of atoms per unit volume,
m = mass of electron,
M_1 = mass of impinging particle,
$\Sigma f_{nl} \ln \frac{4\overline{W}}{A_{nl}} = B$ = deceleration factor. Experimentally determined for several elements and listed on page 374 of Bethe's article.

Using summed values of B determined at constant (room) temperature, we employ the following simplified form of Eq. (1):

$$\frac{v_0^4 - v^4}{p} = \frac{16\pi e^4 z^2 NB}{m^2}, \qquad (2)$$

$m = M_1$ for electron beam,
$z = 1$ for electron beam.

Since: $$v_0^2 = eV/150m \qquad (3)$$

where V = voltage accelerating the electron, then by substituting Eq. (3) in Eq. (2), setting $V = 0$ for total absorption and solving for p, we obtain:

$$p = V^2/(16 \times 2.25 \times 10^4 \pi e^2 NB). \qquad (4)$$

Or: $$p = (3.9 \times 10^{12} V^2)/NB. \qquad (5)$$

Substituting the equality:

$$N = (\sigma N_a)/A \qquad (6)$$

σ = density in g/cm³,
N_a = Avogadros number = 6.06×10^{23} mole^{-1},
A = atomic weight in grams,

in Eq. (5) we obtain:

$$p = (6.48 \times 10^{-12} V^2 A)/B\sigma, \qquad (7)$$

or, for a compound:

$$p = (6.48 \times 10^{-12} V^2 \text{ (M.W.)})/(B_c \sigma N_f), \qquad (8)$$

where (M.W.) = molecular weight of the compound, N_f = number of atoms/molecule and B_c is a weighted average of the B's for the atoms comprising the molecule.

Eqs. (5)–(8) are accurate within the range of 1000 to 30,000 volts, but above 100,000 volts the relativity correction $(1-(v/c)^2)^{-1}$ must be applied to the primary electron's mass.

The elemental values of B may be obtained directly or by interpolation from the experimental data given by Bethe[1] on page 374 of his article. See Table I, which contains elemental N and B values for the elements comprising the luminescent materials being considered.

The molecular values of B_c are calculated as a weighted average from the B's of the component atoms and their numerical ratios.

Similarly, the molecular N may be totalled for each substance; *viz.*, for Zn_2SiO_4:

$$\begin{aligned} N_{Zn} &= 2.28 \times 10^{22} \\ N_{Si} &= 1.14 \times 10^{22} \\ N_O &= 4.55 \times 10^{22} \\ \Sigma N_{Zn_2SiO_4} &= 7.97 \times 10^{22} \text{ atoms/cm}^3. \end{aligned} \qquad (9)$$

Substituting the ΣN and B_c values given in Table II in Eq. (5) we obtain:

TABLE I.

ATOMIC NUMBER	ELEMENT	B(EXPER.)	B(INTERP.)	$N \times 10^{22}$(CALC.)
4	Be		~ 7.8	3.35 ($2BeO \cdot SiO_2$)
8	$1/2O_2$	13.3		6.56 ($2BeO \cdot SiO_2$) 4.55 ($2ZnO \cdot SiO_2$) 5.06 ($CaO \cdot WO_3$)
14	Si		~19.8	1.64 ($2BeO \cdot SiO_2$) 1.14 ($2ZnO \cdot SiO_2$)
16	S		~21.9	2.53 (ZnS) 2.01 (CdS)
30	Zn		~32.5	2.28 ($2ZnO \cdot SiO_2$) 2.53 (ZnS)
48	Cd		~38	2.01 (CdS)
74	W		~47	1.26 ($CaO \cdot WO_3$)

TABLE II.

LUMINESCENT MATERIAL	σ	B_r(AVERAGE)	ΣN
$2BeO \cdot SiO_2$	2.98	12.66	11.55×10^{22}
$2ZnO \cdot SiO_2$	4.218	19.70	7.97×10^{22}
ZnS	4.09	27.20	5.06×10^{22}
CdS	4.82	29.95	4.02×10^{22}
$CaO \cdot WO_3$	6.06	20.87	7.595×10^{22}

$$p_{Be_2SiO_4} = \frac{3.9 \times 10^{12} V^2}{12.66 \times 11.55 \times 10^{22}} = 2.68 \times 10^{-12} V^2 \text{ cm}, \quad (10)$$

$$p_{Zn_2SiO_4} = \frac{3.9 \times 10^{12} V^2}{19.7 \times 7.97 \times 10^{22}} = 2.5 \times 10^{-12} V^2 \text{ cm}, \quad (11)$$

$$p_{ZnS} = \frac{3.9 \times 10^{12} V^2}{27.2 \times 5.06 \times 10^{22}} = 2.83 \times 10^{-12} V^2 \text{ cm}, \quad (12)$$

$$p_{CdS} = \frac{3.9 \times 10^{12} V^2}{29.95 \times 4.02 \times 10^{22}} = 3.24 \times 10^{-12} V^2 \text{ cm}, \quad (13)$$

$$p_{CaWO_4} = \frac{3.9 \times 10^{12} V^2}{20.87 \times 7.595 \times 10^{22}} = 2.46 \times 10^{-12} V^2 \text{ cm}. \quad (14)$$

Using Eqs. (10)–(14) we have calculated the penetration distances into these listed luminescent materials, for various voltages, and tabulated the data in Table III.

One would predict from the data of Table III that sulphide screens should be made 13–30 percent thicker than screens made of the listed oxide phosphors (luminescent materials). This prediction finds experimental verification in practice.

III. DIRECT VIEWING CR SCREENS

Screen production for CR tubes viewed on the scanned side of the luminescent screen is relatively simple in that screen thickness is not critical as long as the screen thickness is made considerably greater than the penetration distance given in Table III for a particular voltage and material. The luminescent spot size is a minimum for this type of screen and, as a result, image definition and contrast is at its best.

In the absence of single-crystal sheets of luminescent materials, the question of optimum particle size will be considered specifically for the following case of indirect viewing screens. The luminescent particles (a_p) may be made to firmly adhere to the metal or glass base member (b, Fig. 2) by using suitable binders (Na_2SiO_3, K_2SiO_3) or by partially embedding some of the luminescent particles in a molten vitreous medium such as B_2O_3 and allowing the vitreous base to cool, whereupon it contracts and interlocks adjoining particles as shown in Fig. 3.

IV. INDIRECT VIEWING CR SCREENS

With the present, normal type of CR tube the image is viewed, or projected, from the side of the cathodoluminescent screen which is opposite to the side being scanned by the electron beam. A cross-sectional view of this type of screen arrangement is shown in Fig. 4 where the screen is shown in the ideal form of a transparent section from a large single crystal of luminescent material.

The electron beam of average intensity $(V \cdot I)/\pi a^2$ (V = voltage accelerating electrons to the screen, I = total current carried by the electron beam, and a = radius of the beam) impinges upon the luminescent material, whereupon the electrons are scattered and decelerated by collisions with crystal units and interaction with lattice forces. Upon deceleration, the primary electrons' energy losses are transformed into secondary electrons, high frequency electro-

TABLE III. *Penetration (p) in μ($1\mu = 10^{-4}$cm $= 0.001$ mm $= 10^4 A$).*

VOLTAGE V	$2BeO \cdot SiO_2$ $p(\mu)$	Zn_2SiO_4 $p(\mu)$	ZnS $p(\mu)$	CdS $p(\mu)$	$CaWO_4$ $p(\mu)$
100	0.00027	0.00025 (2.5A)	0.000283	0.000324	0.000246
1000	0.027	0.025 (250A)	0.0283	0.0324	0.0246
2000	0.107	0.10 (1000A)	0.113	0.13	0.0984
3000	0.241	0.225	0.254	0.292	0.222
4000	0.429	0.40	0.45	0.52	0.394
5000	0.67	0.655	0.71	0.81	0.615
6000	0.965	0.90	1.02	1.17	0.885
7000	1.31	1.225	1.39	1.59	1.215
8000	1.72	1.60	1.81	2.08	1.58
9000	2.17	2.02	2.30	2.62	2.00
10,000	2.68	2.50 (25,000A)	2.83	3.24	2.46
15,000	6.16	5.65	6.37	7.30	5.54
20,000	10.72	10.0	11.32	12.96	9.84
30,000	24.1	22.5	25.4	29.2	22.2
50,000	67.0	65.5	71.0	81.0	61.5
100,000	268.0	250.0	283.0	324.0	246.0

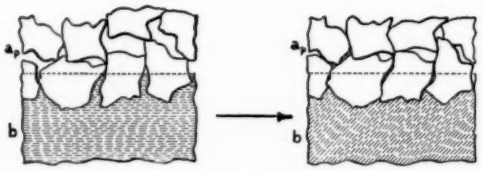

FIG. 3. Section illustrating the preparation of a luminescent screen by partially embedding phosphor particles in a vitreous medium.

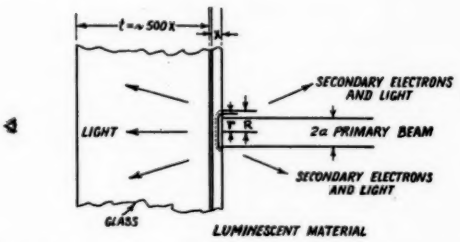

FIG. 4. Section through an "ideal" luminescent screen.

magnetic radiation, photoelectrons, and heat energy in the crystal. The secondary electrons, soft x-rays, ultraviolet radiation, and photoelectrons scatter in all directions and may be the principal exciting agents for the desired visible (or actinic) radiant energy. The electron beam cross section (πa^2) is, therefore, always smaller than the luminescent spot (πr^2). The radius "r" represents an outer limit of visible intensity corresponding to a certain value of the quantity $(V \cdot I)/\pi a^2$. The distance $r-a$ increases in size as the current (I) is increased since the scattered primary and secondary energy per unit volume increases in the annular region ($r-a$) around the projected primary beam within the crystal, thus increasing the intensity of emitted visible light and making a formerly invisible outer region of the luminescent spot brilliant enough to be observable.

Conversely, the distance $r-a$ decreases as a is increased (keeping V and I constant). The quantity $r-a$ would be expected to decrease with increasing V only if the screen thickness x were less than the penetration distance of the electrons (p) and if the primary electrons contribute the bulk of luminescence excitation energy, since the scattering of primary electrons decreases with increasing velocity. One should, therefore, expect an increase of $r-a$ with: 1. Increase of either I or V, or, 2. A decrease of a while holding the remaining two variables constant. This relationship between visible spot and beam diameter holds true until the energy density $(V \cdot I)/\pi a^2$ is sufficient to cause saturation or destruction of luminescence power (commonly known as "burning") of the particular luminescent material of which the screen is composed.

Spurious rings, which are attributed by J. V. Hughes[2] to multiple reflections in the transparent supporting member, are not considered in the above discussion, but may be minimized by keeping the glass thickness small and avoiding the use of binders in screen production.[3]

If we had large transparent single crystals of our luminescent materials, the screen thickness "x" would be immaterial, except as affecting the spurious rings. In such an ideal case the light output and contrast would then depend only upon the characteristic efficiency of the phosphor, the beam diameter and reflection losses at the boundary surfaces of the glass and screen. It is a moot question whether the increased efficiency which could be obtained by using transparent sheets of luminescent materials would be more than offset by a loss in heat-radiating surface. Small particles have the definite advantage of a relatively large surface from which to radiate secondary heat energy which represents 95 percent or more of the primary beam energy.

In any event, it is with small crystals that we are at present making luminescent screens and the considerations affecting attainment of optimum luminescence efficiency are presented in the following.

An actual, indirectly viewed screen cross section is shown drawn to scale in Fig. 5. The primary electron beam carries $100\mu A$ at 10,000 V with an observed luminescent spot diameter of 0.1 mm ($=2b$). In 9" Kinescopes used for television, operating at 6000 volts with $75\mu A$ beam current, the spot size for a 343 line image averages about 0.7 mm diameter, or seven times as large as shown in Fig. 5.

From Table III we find that the penetration distance (p) of 10,000 volt electrons into certain phosphors is: 2.5–3.2μ ($=0.0025$–0.0032 mm)

[2] Proc. Phys. Soc., pp. 434–441, May 1 (1933).

[3] See also, M. von Ardenne, Hochfreq. u. Elektroakustik **46**, 1, 1–4, July (1935).

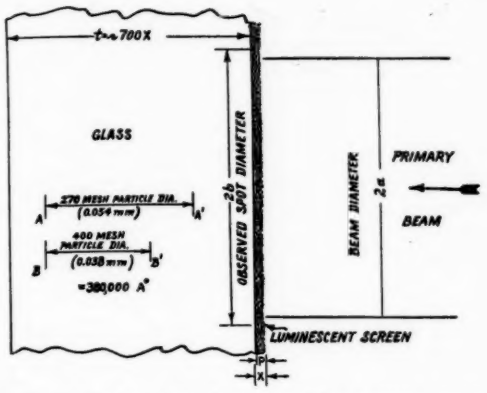

FIG. 5. Section through an actual luminescent screen. The thickness t would be 1.42 meters at this magnification. Scale: 1 mm = 0.00238 mm.

depending upon the phosphor. The effective beam penetration (p) is a function of beam current density just as the visible spot size is also a function of current density ($I/\pi a^2$), since the electrons are exponentially attenuated in energy, as they pass through the luminescent material, and a phosphor region at the electron penetration limit may be brought from formerly unobservable intensity to detectable brilliancy by increasing the energy density in this region as a consequence of increasing the primary beam current density.

Having determined the approximate penetration of our primary electrons for a particular screen we next proceed to the problems of optimum particle size and optimum screen thickness. We shall use synthetic willemite, $2ZnO \cdot SiO_2$: Mn, as an illustrative example.

A candlepower *vs.* applied voltage curve for a $2ZnO \cdot SiO_2$: Mn screen, as measured with a Macbeth illuminometer using a suitable calibrated Wratten filter and keeping the beam current constant, is shown in Fig. 6. The graphical relationship follows a modified Lenard's[4] equation:

$$L = K_1\varphi(I, a)(V_A - V_0) - K_2 f(V),$$

L = luminous intensity (candlepower),
K_1 and K_2 = constants characteristic of the phosphor,
I = beam current, (15)
a = beam radius,
V_A = applied voltage,
V_0 = "dead" voltage (see Fig. 5),
$-K_2 f(V)$ = secondary emission function (to be discussed later).

[4] Ann. d. Physik **12**, 462 (1903).

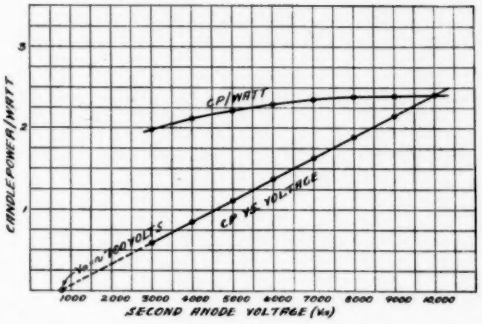

FIG. 6. Candlepower voltage relationship for an indirectly viewed $2ZnO \cdot SiO_2$: Mn screen. Scanned area, 6×8 cm^2. Beam current = 100μA.

The quantity V_0 has been termed "dead" voltage and was first interpreted by Lenard and Saeland[5] as caused by inactive surface layers of the luminescent particles. These layers do not luminesce efficiently, but nevertheless absorb energy and necessitate a certain minimum voltage V_0 for penetration through to the active interiors of the luminescent particles.

In the present case of $2ZnO \cdot SiO_2$: Mn it is seen that V_0 equals $\sim$700 volts, $p_0 = 0.000012$ mm (0.012μ) (from Eq. (12)). As is shown in Fig. 6, V_0 is an extrapolated quantity and does not represent the lowest voltage at which $2ZnO \cdot SiO_2$: Mn particles will luminesce if subjected to extremely high current density. Experiments conducted by H. C. Thompson at the Radiotron division of the RCA Manufacturing Co., Inc. showed luminescence of $2ZnO \cdot SiO_2$: Mn as low as 12 volts when subjected to enormous current densities.[6]

The question of optimum particle size (y) is made complex by the random orientations and multireflections encountered in the screen. If the observer were to view the screen from the same side as it is scanned, the particle size (y) would be made large (up to $\sim 1/10$ the beam diameter—larger particles would give the image a definite "grain") and the screen thickness (x) would be made equal to several times the penetration (p) of the electrons. Thus, the number of internal reflections of the emitted light would be reduced, the number of "dead" voltage layers per unit volume would be de-

[5] Ann. d. Physik **28**, 485 ff (1909).
[6] Communicated by Dr. L. B. Headrick.

creased and the ample excess screen thickness would assure complete utilization of all the primary and derived secondary energy. However, since the emitted light must suffer many reflections before emerging through to the glass, the distance (x) must be reduced to an optimum depending upon both (p) and (y).

The problem of transmission of light through a suspension of randomly orientated particles has been worked out by B. Mukhopadhyay.[7] The expression shows, in agreement with experiment, a much smaller transmission for a suspension of doubly refracting particles than for those of an isotropic body.[8]

For crystalline powders:

$$L = L_0 \exp -\frac{4\pi^2}{\lambda}\left[(\mu_0-\mu)^2\left(\frac{\pi}{8}-\frac{\pi^2}{36}\right) + (\mu_e-\mu_0)^2\left(\frac{\pi}{30}-\frac{\pi^2}{324}\right) + (\mu_e-\mu_0)(\mu_0-\mu)\left(\frac{\pi}{12}-\frac{\pi^2}{54}\right)\right]\cdot x\cdot y \quad (16)$$

L = intensity of light encountering the nth layer,
L_0 = initial intensity,
y = diameter of the particles,
x = total thickness (n.y),
n = total number of layers,
λ = wave-length of the light,
μ = refractive index of fluid (vacuum),
μ_0 = " " " ordinary vibration,
μ_e = " " " extraordinary vibration.

$$\mu_e > \mu_0 > \mu.$$

The relative scattering powers of small particles are numerically given in Table IV.[9]

From the above Eq. (16) we perceive that to increase L, we should:

(1) Decrease (x), (y), (μ_e) and (μ_0).
(2) Increase (μ) and (λ).

The only variables which we can appreciably affect are (x), (y) and (λ).

Variation of (λ) requires shifting the luminescence spectrum, such as by polymorphic transition[10] or by the substitution of Cd for Zn in ZnS : Cu, ZnS : Ag or $2ZnO\cdot SiO_2$: Mn, and is not to be discussed in the present article.

Of the two remaining variables, (x) and (y), we have a definite lower limit for (y). This lower limit is the smallest producible crystal of luminescent material which is still capable of appreciable luminescence. It is obvious that, for $2ZnO\cdot SiO_2$: Mn, we should not decrease (y) below $\sim 2(0.000012)$ mm = approximately 0.000024 mm because the entire crystal would then be "dead" as far as luminescence is concerned (since the "dead voltage" penetration (p_0) is approximately 0.000012 mm). It is also obvious that the particle size should be such that the ratio of luminescent volume to nonluminescent volume is efficiently large (10 times or more). Numerically expressed, this volume ratio, for either spheres or cubes, fits the general equation:

$$10[y^3-(y-2p_0)^3] \geq (y-2p_0)^3 \quad (17)$$

or:

$$y_{\min.} \geq 64p_0. \quad (18)$$

$64p_0$ for $2ZnO\cdot SiO_2$: Mn is approximately 0.00077 mm or about 3/4 the average particle size as shown in Fig. 5. The "dead voltage" value of 700 volts, from which p_0 was calculated, is probably too large since the curve slope (Fig. 6) is affected by the secondary emission factor $-K_2 f(V)$ and, furthermore, the cumulative effect of the beam traversing 2–3 particles, each with "dead voltage" layers, should actually reduce the true p_0 per particle to approximately 200 volts, whereupon $p_0 = \sim 0.000001$ mm and $64p_0 = 0.000064$ mm or 1/15 of the particle diameter shown in Fig. 5. The inactive thickness p_0 should increase as y decreases because the relative surface distortion energy of the particles will increase upon volume diminishment. It will be appreciated that means of comminution play an important part in affecting p_0, especially with the less rugged sulphide luminescent materials.

Having established at least the lower practical optimum magnitude for y, we now investigate the optimum screen thickness x. Experimental determinations, Fig. 7, established an optimum screen thickness, under the conditions described in connection with Fig. 5, of $x = 0.7$ mg $2ZnO\cdot SiO_2$: Mn/cm^2. The average compact, effective thickness x_e of such a screen is:

$$x_e = (0.0007 \times 10^4)/4.2 = 1.66\mu. \quad (19)$$

[7] Indian J. Phys. **7**, 307–315 (1932).
[8] The materials listed in Table III are all weakly birefringent.
[9] W. M. Hampton, J. Soc. Glass Tech. **16**, 401 (1932).
[10] Schleede and Gruhl, Zeits. f. Elektrochem. u. angew. Physik. Chem. **29**, 17/18, 411–412 (1923).

Since the actual material thickness is only 1.66μ and, from Table III, the penetration of a 10,000 volt electron beam is 2.5μ, we have a discrepancy of:

$$2.5\mu - 1.66\mu = 0.84\mu. \qquad (20)$$

Therefore, it would appear that, for an applied potential of 10,000 volts, the electrons are passing entirely through the luminescent screen and bombarding the glass tube wall. However, discounting any error in the data of Table III, it is more likely that the effective accelerating potential (V) on the screen is only 8200–9000 volts ($p = 1.66$–2μ). The higher values are indicated by the finding of Lange and Brasch[11] that CR rays lose most of their energy in approximately 1/3 of the distance to which they can penetrate matter. This viewpoint finds experimental verification in investigating secondary emission processes. The voltage at which secondary emission equilibrium (i.e., when the number of primary electrons equals the number of secondary electrons) takes place on a dielectric powder, placed as shown in Fig. 5, is normally lower than the applied voltage and measurements have indicated a difference $-K_2 f(V)$ as large as 1500 volts for $V_A = 10{,}000$ volts (Schnabel[12] finds a difference of 2000 volts for $V_A = 8000 V$). The value of $-K_2 f(V)$ is dependent upon the phosphor and upon V_A; since the secondary emission ratio above about 300 volts decreases as the primary electron penetrations increase. Accurate quantitative measurements of the effective voltage, $V = (V_A - K_2 f(V))$, accelerating the electrons to the screen have not been made, but the optimum screen thickness x gives us an approximate indirect determination of this quantity since:

$$x \leqq p_{(V_A - K_2 f(V))} \qquad (21)$$

for a certain beam current density and scanning frequency.

TABLE IV.

Particle Diameter	Rel. Scattering Powers Constant Volume of Particles	Constant Number of Particles
0.2×10^{-2} mm	125	1
0.5	690	87
1.0	1730	1730
2.0	3470	35000

[11] Strahlentherapie **51**, 119 (1934).
[12] Archiv. f. Elektrotechnik **28**, 794 (1934).

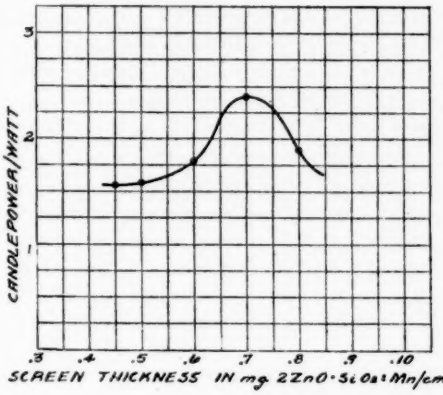

FIG. 7. Experimental determination of optimum screen thickness for a given applied voltage (V_A), beam current (I), and pattern area (S)

$V_A = 10{,}000$ volts. $I = 100\mu A$. $S = 6 \times 8$ cm².

Having determined that optimum screen thickness is dependent upon both beam current density ($I/\pi a^2$) and actual accelerating voltage (V), we next consider the problem of obtaining luminescent materials with very small particle size (y).

V. Comminution of Luminescent Materials

Solid, inorganic luminescent materials are very sensitive, complicated latticeworks. Drastic localized actions such as mechanical stress or chemical attack seriously disturb their delicate atomistic mechanisms, reducing their efficiencies as converters of high energy excitation (cathode rays, x-rays, ultraviolet light) into lower energy radiant emission (e.g., visible light). It is usually necessary to reduce the particle size of freshly-synthesized phosphors to about 1/100 of their original diameter (~0.1 mm) in order to obtain particles small enough to adhere to the glass without resorting to a binder. The task of grinding a luminescent material should be accomplished with as little mechanical force as is necessary to split the large crystals into smaller fragments without appreciable reduction of luminescence efficiency or increase of the inactive layers (p_0) per unit volume.

Sulphide phosphors are not only much less chemically stable, but are also less physically stable than oxide phosphors. Schleede and

Gantzckow[13] have determined a distinct structural inversion from wurtzite to sphalerite upon grinding zinc sulphide. Sulphide phosphors must, therefore, be used "as synthesized" in order to retain their original good efficiencies and to avoid changing their spectral distributions. Reheating of comminuted sulphides is usually less practicable than making the original particles as small as possible by skillful crystallization, especially with certain beneficial fluxes such as halides of the elements in vertical groups I or II of the periodic system.

Grinding of oxide luminescent materials, such as $2ZnO \cdot SiO_2$: Mn, $2BeO \cdot SiO_2$, and $CaO \cdot WO_3$ is conveniently possible because of the great stability of oxide compounds.

It has been our practice to comminute synthetic $2ZnO \cdot SiO_2$: Mn in a transparent fused quartz ball mill, Fig. 8, using small quartz balls. The Moh hardness of $2ZnO \cdot SiO_2$: Mn is 5.5 and it was found that Pyrex glass ball mills and balls were rapidly ground away, whereas fused silica (hardness on Moh scale = 7), suffered no apparent scorification. Ball milling has the advantage of tending to produce a uniform particle size in that the smallest particles are washed away from beneath a falling, or preferably sliding, ball leaving the larger particles to be broken.

Suitable fluids for use in the ball mill include many relatively inert organic liquids such as ethers, alcohols, acetates and ketones, as well as distilled water with or without certain easily volatilized electrolytes such as carbon dioxide, ammonium carbonate and ammonium hydroxide.

The ball mill is rotated at such a speed that the balls slide instead of tumbling and the milling is continued until the rate of fall of the particles in the fluid decreases to a value which may be approximately calculated from Stokes' law:

$$\begin{aligned} &v_m = (2r^2zg)/9s, \\ &v_m = \text{rate of fall (cm/sec.)}, \\ &r = \text{radius of falling sphere (assumed)} = \tfrac{1}{2}y, \\ &z = \text{density of the sphere (4.218 for } 2ZnO \cdot SiO_2 : Mn), \\ &g = \text{gravitation constant} = 981 \text{ cm/sec.}^2, \\ &s = \text{coefficient of viscosity of the fluid} = 0.002 \text{ for ether}, \end{aligned} \tag{22}$$

100 to 200 hour grinding in ether yields suspensions such that $v_m = 0.020$ cm/sec. (3 mm in 15 seconds). Substituting $v_m = 0.02$ in Stokes' equation, rearranged to solve for y:

$$y = 6[(sv_m)/(2zg)]^{\frac{1}{2}} \tag{23}$$

we obtain a value of $y = 0.004$ mm, which is in fair agreement with the microscopically measured average value of $y = 0.001$ mm, even though aggregation, electrostatic charging, nonuniformity and deviation from sphericity have not been taken into consideration. The luminescent material so comminuted may be dried and stored, or made up directly into a suitable spraying or settling suspension.

VI. Screening

Spraying suspensions may be made with many highly volatile organic fluids, with or without easily removable temporary binding ingredients such as nitrocelluloses or acetates. Sprayed screens are entirely practical and economical to prepare, but lack the tenacity and uniformity of the settled screens to be described later. Satisfactory screens may be prepared also by simple "dusting" or settling of the finely divided phosphor powder in the air upon a clean glass or metal surface. Atmospheric conditions and electrostatic charging greatly affect the dusting process and the resultant screens are subject to the same criticisms as sprayed screens.

Screens may be accurately settled in a liquid medium, such as water, which is subsequently poured off the settled screen by means of a machine shown in Fig. 9. This screening method has been in use for over six years and allows consistent, controllable production of uniform cathode-ray tube screens which, notwithstanding the complete absence of any binder, may be subjected to the full force of water from a faucet without dislodging the settled particles. The following considerations apply to the settling suspension and method.

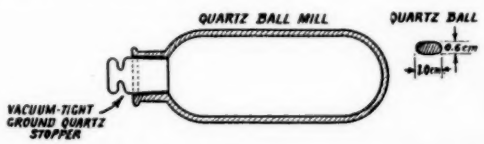

Fig. 8. Section through quartz ball mill used for comminuting luminescent materials.

[13] Zeits. f. Physik **15**, 184–189 (1923).

(A) Liquid settling suspensions

The ideal settling suspension should contain the luminescent material in separate, non-aggregate particles which may be shaken into homogeneous distribution throughout the liquid and which will then descend under the influence of gravitational force along (except as influenced by Brownian movement) without any local or spatial charges accumulating in the fluid suspension. Furthermore, the settling solution should not strongly react with the phosphor or with the glass or second anode coating in the CR tube.

It is advisable to use settling liquids of low viscosity (w) and high surface tension (q).[14] Low viscosity decreases the frictional force upon the settled screen during pouring and insures high ionic mobilities for the added electrolytes (explained in the following). High surface tension (q) is desirable in order to have the surface of the liquid as pure as possible and thus decrease "wetting" and other adsorption phenomena during settling and pouring. The relationship between surface tension and surface purity is expressed by Gibb's (1877) equation:

$$a = -\frac{c}{RT}\cdot\frac{d(q)}{d(c)}, \qquad (24)$$

a = excess or deficiency of number of moles (of solute) in the unit surface, as compared with,
c = average concentration of the entire solution,
R = the universal gas constant,
T = the absolute temperature.

Therefore, capillary active substances (alcohols, fatty acids and their esters) which lower (q) with increasing concentration ($[d(q)/d(c)]<0$) are adsorbed in the surface layer[15] ($a>0$); whereas, capillary inactive substances (most electrolytes and albuminoids) which increase (q) with increasing concentration ($[d(q)/d(c)]>0$) are negatively adsorbed (thrown out) by the surface layer ($a<0$).

Gibb's law also shows that high concentration, c, of capillary inactive electrolyte (solute) and low temperature, T, of solution are favorable to the desired purity of the surface liquid.

We have previously mentioned that our present average particle size (y) of the ground $2ZnO\cdot SiO_2$: Mn is about 0.001 mm. This small size of particle brings us close to the realm of ordinary pseudocolloids. We must, therefore, observe the physical principles of colloidal phenomena in our settling suspensions. One important empirical law (Coehn, 1898) of colloid physics is:

If a colloidal dispersion consists of two dielectrics, the substance having the greater dielectric constant (ϵ) charges itself positively (i.e., loses electrons) with respect to the substance of lower dielectric constant.

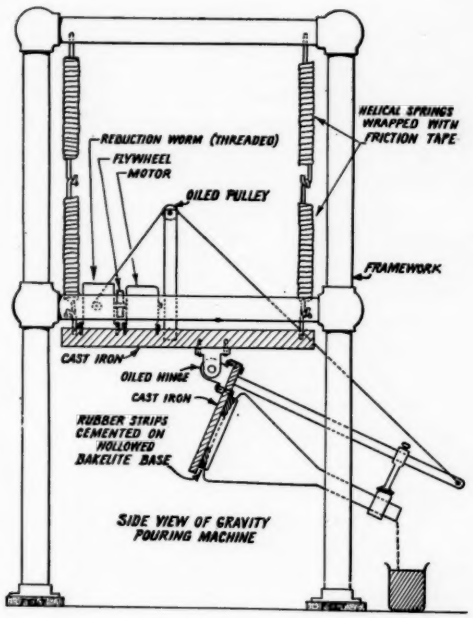

FIG. 9. Section through gravity pouring machine used for decanting suspension liquid.

[14] Silverman and Roseveare, J. Am. Chem. Soc. **54**, 4460 (1932), give an equation relating viscosity and surface tension:

(a) $W = E'/(V_s - L_L)$ = viscosity,
(b) $q = E(D-d)^4$ = surface tension,
E' and E = constants for a given liquid,
V_s = specific volume,
V_L = limiting volume (or approximately van der Waal's "b"),
D = density of the liquid,
d = density of the vapor.

Neglecting d and equating V_s to $1/p$, we obtain:

(c) $q^{-1/4} = E_1(1/W) + E_2$, or: $W = \dfrac{E_1}{\dfrac{1}{4\sqrt{q}} - E_2}$,

where E_1 and E_2 are constants characteristic of the liquid. The equation holds true for 25 liquids (water included), but deviates as the fluidities of the liquids decrease.

[15] Comptes rendus **194**, 1076-1077 (1932).

Note: Water $(\epsilon)=80$; $2ZnO\cdot SiO_2 : Mn(\epsilon) = \sim 15$.

We had been using very pure, distilled water, $(W)=0.01005$ (20°C), $(q)=72.75$ (20°C), for our settling liquid and experienced no serious difficulty in *settling* screens until we decreased our particle size from approximately 270 mesh (0.05 mm) to far less than 400 mesh (0.001 mm), in order to reduce pouring failures. Immediately after the decrease in particle size, we encountered a period of trouble during which the settled screens looked like the force lines traced by a myriad of tiny iron filings in an inhomogeneous magnetic field. Vigorous shaking failed to eliminate streamer-like volumes, approximately 1/16″–1/4″ wide, which were visibly distinguished by having very few suspended particles. The problem of eliminating the charges which were evidently accumulating throughout the solution was first solved by saturating water with carbonic acid evolved from solid carbon dioxide ("dry ice"). Complete saturation yielded excellent results as long as the temperature was low and the dry ice particularly pure and oil-free. The reaction:

$$\begin{array}{l} CO_2+H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \\ \qquad\qquad\qquad\qquad\qquad\quad \Updownarrow \\ \qquad\qquad\qquad\qquad\qquad\quad H^+ + CO_3^= \end{array}$$

yielded enough high mobility hydrogen ions to discharge the negatively charged phosphor particles as fast as they formed on falling through the solution. Pure water is unable to do this, since the dissociation constant of pure water is only 10^{-14}, whereas the dissociation constant for the first H^+ of carbonic acid is 3×10^{-7}, and for the second H^+ is 6×10^{-11}.

We have discontinued the use of carbonic acid because pure, oil-free, solid carbon dioxide is not commercially obtainable and it is difficult to prevent explosions of saturated carbonic acid solutions in glass-stoppered bottles. In its place we are now using ammonium carbonate, (carbamate) $NH_4HCO_3NH_4NH_2CO_2$, which is even more satisfactory by virtue of its high solubility (thus increasing (q) in Eq. (24)), and high dissociation without the disadvantage of explosive qualities. The aqueous ionic reactions for ammonium carbonate carbamate are given below:

$$\begin{array}{l} 2NH_4HCO_3NH_4NH_2CO_2+2HOH \rightleftarrows \\ \qquad\qquad 3(NH_4)_2CO_3+H_2CO_3 \\ \qquad\qquad\quad \Updownarrow \qquad\quad \Updownarrow \\ \qquad 6(NH_4)^+ + 3CO_3^= H^+ + HCO_3^- \\ \qquad\qquad\qquad\qquad\quad \Updownarrow \\ \qquad\qquad\qquad\qquad H^+ + CO_3^=. \end{array}$$

Other easily volatilized electrolytes, such as ammonium halides, ammonium acetate, ammonium hydroxide, and weak acids such as acetic acid, have been employed with varying success, but ammonium carbonate has given the best results to date.

Further advantages of the ammonium carbonate solutions are:

1. Many phosphors may be comminuted in a concentrated aqueous solution of ammonium carbonate, and thereupon diluted directly to form the desired concentration of settling suspension. Aggregates formed when ground phosphors are dried from an organic liquid, and which must be dispersed by remilling with very small balls or pure, round (*viz.*, Ottawa) quartz sand, are thereby obviated.

2. The slightly alkaline solution of ammonium carbonate serves a twofold purpose:

(*a*) A very slight surface decomposition of the phosphor particles may be made to occur whereupon the inactive layers (p_0) may be diminished or allowed to recrystallize with lessened localized stresses. This action seems to proceed best in mildly alkaline solutions, but the decomposition may be accomplished also by weak acids.

(*b*) The slight surface chemical action (decomposition and/or hydrolysis) produces an active surface, particularly upon silicate phosphor particles. Such an active surface readily interacts with the siliceous[16] surface of glass and, upon drying and heating, forms an additional bond which may sometimes exceed the normal adhesive forces, which latter are presumably of the van der Waals or field valency type of attraction.

In practice, we make suspensions having phosphor concentrations ranging from 0.002–0.020 gram/ml of water, triple distilled in Pyrex. The ammonium carbonate (carbamate) concentration is made constant with respect to the phosphor concentration and has been found to be most effective in the ratio of 12.5 grams of ammonium carbonate carbamate to each gram of comminuted phosphor having an average particle size of 0.001 mm.

The suspensions are kept in Pyrex, glass-stoppered bottles, stored in a refrigerator at 2–4°C, and should be agitated at least once a week if not in constant use.

[16] Keram. i. Steklo **7**, No. 11–12, 36–41 (1931).

(B) Pouring the settled screen

The pouring process may be conveniently accomplished with a comparatively vibration-free machine such as the one sketched in Fig. 9. A small beaker of mercury placed upon the heavy iron pouring platform should show no surface ripples during the pouring operation. The room in which the pouring machine is located should be kept at a reasonably constant cool temperature (10–15°C) in order to assure purity of the surface liquid, minimize Brownian movement and prevent "loading" of the screen in the center or at the edges. The "loading" effect is caused by large changes or differences of temperature between the original suspension and the air outside of the tube. Such large differences cause convection currents at the inner glass surface and seriously interfere with normal settling. A small, controlled room temperature decrease during the settling operation may be calibrated to compensate for a variation in suspension height from the center to the outer edge of the screen. The same uniform settling result may be more easily obtained by accurately controlling the initial room- and suspension-temperatures, such that the former is lower than the latter by an amount depending upon the CR blank size and geometry.

An accurately measured volume of well-shaken suspension may be pipetted from the cold "stock" previously described (*A*), diluted and well mixed with distilled water which is kept at a controlled temperature, and poured into the *clean* CR tube blank. The blank is placed in an upright position on the pouring machine (Fig. 9) and the suspended particles allowed to settle upon the broad end of the blank. After three to eight hours, depending upon the particle size and suspension height, there should be no Tyndall effect noticeable when a narrow beam of light horizontally traverses the suspension liquid. If the Tyndall effect test is satisfactory, the pouring machine may be turned on and allowed to slowly decant the liquid in 30 to 40 minutes. When the liquid has been poured, the tube may be immediately removed and the screen dried with a current of warm, filtered air.

The resultant screens have the following advantages:

1. There is no waste of luminescent material such as occurs in spraying.
2. The screens are uniform and have a *known* thickness which may be accurately controlled to give optimum luminescence efficiencies for particular beam voltages and beam current densities.
3. No binder is used in applying the phosphor particles, yet the screens are surprisingly adherent.
4. The slightly acid or alkaline settling suspension may be used to reduce "dead voltage (V_0)" by decreasing the thickness (p_0) of the "dead" outer layers of the phosphor particles.

In conclusion, the writer acknowledges excellent experimental assistance afforded by Mr. H. W. Rhoades and the generous advice and encouragement given by Dr. V. K. Zworykin, Director of Electronic Research.

The Visibility of Radiation at Low Intensities*

K. S. WEAVER
Eastman Kodak Company, Rochester, New York
(Received November 14, 1936)

A visibility curve depending on about 15 observers has been taken at an intensity comparable to the lowest used in darkroom work. A series of determinations of the wave-length of maximum visibility for several intensities and observers has also been made giving a curve extending from near the dark adapted threshold to about 2 foot lamberts. The observations were all made with the natural pupils and binocular vision. Comparisons with some previous work of other authors are made. The wave-length of maximum visibility at the highest intensity corresponds very closely with that of the standard I.E.S. photopic curve. At the lower levels, values are found approximating those given by König in his complete curve, and by Hecht for an intensity 2.7 times the dark adapted threshold.

PHOTOMETRY at very low levels is required in checking the illumination in the various work rooms, in which unprotected photographic materials are processed or inspected, and in the experimental work involved in the development of safe lights.

Jones and Lowry[1] have designed a low brightness photometer especially for this work.

The field of view is a large white disk which receives the illumination to be measured. A hole through the center of this disk covered with a diffusing glass of low reflection factor is used to permit the light from a comparison source to be seen. This type of field, which is observed binocularly without artificial pupils, can be used at very low intensities and is thought to reproduce adequately actual seeing conditions under low illumination.

Since the visibility function is of fundamental importance in photometry, it was thought desirable to secure more data on the visibility function, under the specified conditions of observation, than were available in the literature. While many investigations of the visibility function under various conditions have been made, most of them have been carried out with monocular vision through an artificial pupil (usually the exit slit of a spectrograph or its image). In some cases, measurements were made at only one intensity; in other cases, at several.

It was planned, therefore, to determine the visibility function for a number of observers using a circular field, natural pupils, and binocular vision, at a low intensity approximating that used in handling high speed panchromatic materials, and to determine the shift of the wave-length of maximum visibility as the intensity varied.

Choice of a Field

In selecting the size and pattern for the field, its suitability for use at the low level (about 6.5×10^{-5} foot lamberts) at which most of the work was to be done must be considered. It was further required that the field adopted could be used, at least with fair precision, at lower as well as at higher intensities.

The alternative of trying to select an optimum field for each intensity in order to obtain the best conditions of observation was rejected as unduly complicating the problem. As a compromise, a circular disk, with a small hole in the center, was cut from white blotting paper. At the viewing distance, which was 11 inches, the diameter of the disk and of the central aperture subtended angles of 14 degrees and 2.6 degrees, respectively, at the eye of the observer. A comparison source illuminated the blotting paper, and the central opening was illuminated by the light from a spectrometer reflected from a block of magnesium carbonate. After some preliminary work, it was decided that the addition of a cross bar (shown in the drawing of the field in Fig. 1) would improve the precision at the higher intensities, and this form was subsequently chosen.

Adaptation of the Eye

All the data were taken with the eyes adapted to the light from the comparison field, at the

* Communication No. 604 from the Kodak Research Laboratories.

[1] L. A. Jones and E. M. Lowry, "A Photometer for the Measurement of Low Illuminations," Trans. Soc. Mot. Pict. Eng. **12**, 1054 (No. 36) (1928).

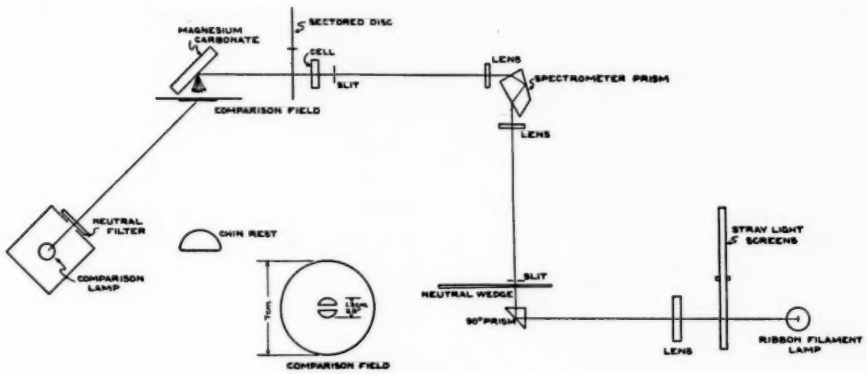

FIG. 1. Arrangement of apparatus used for the visibility determination.

intensity at which the photometric measurements were to be made.

The time required for satisfactory adaptation varied from about ten minutes at the higher levels to one hour at the lowest level, which was approximately ten times that of the dark-adapted threshold.

MEASUREMENT OF THE COMPARISON FIELD BRIGHTNESS

The comparison field brightness was measured at a high level, using a Macbeth illuminometer calibrated in foot lamberts.[2] Lower levels were reached by using a series of neutral gelatin filters over the comparison lamp. The values at the lower intensities were calculated from the measured high intensity and the densities of the neutral filters.

Our intensity scale is thus based on the use of a heterogeneous source (color temperature about 2500°K) reduced by a neutral medium of known absorption.

METHOD OF COMPARISON

The equality of brightness rather than the flicker method of comparison was used as the only one suitable for a wide range of intensities. At the low intensity at which most of the data were taken, the eye is not very sensitive to flicker, and the color difference between the monochromatic and the comparison side of the observational field is too low to affect seriously the precision of the settings, except possibly in the red.

GENERAL ARRANGEMENT OF APPARATUS

The arrangement of the apparatus is shown in Fig. 1. A ribbon lamp filament was imaged on the entrance slit of a Hilger spectrometer. The intensity of the light was controlled by an uncalibrated neutral wedge placed over the entrance slit. The amount of stray light was reduced by using suitable Wratten filters carried on a circular disk in such a way that the proper one for a given wave-length could be quickly set in place. After passing through the exit slit of the spectrometer, the light illuminated the surface of a block of magnesium carbonate over the area seen by the observer as the central portion of the comparison field.

In making a setting, the observer simply moved the neutral wedge on its slide until a balance was obtained. The photo-cell was then lowered in place so as to intercept the light, and the deflection of the galvanometer to which it was connected was recorded. Such a measurement with the photo-cell was made after each setting of the wedge.

The use of the photo-cell instead of a thermocouple for the energy measurements made it feasible to make such frequent measurements of energy, since the response of the cell is much more

[2] Although the use of illumination units rather than brightness units in specifying field brightness is quite common in this kind of work, it seemed to the writer that a certain amount of confusion results, even when the surface on which the comparison illumination falls is specified.

rapid, and the cell is not disturbed by such variations in room conditions as would cause erratic behavior in a thermocouple. In this procedure, the accuracy of the result depends on the accuracy with which the cell has been calibrated, but no further calibration, either of the neutral wedge or of the source of light, is required. It is only necessary that the lamp be held constant over the period of time required for one setting by the observer and the corresponding energy measurement by the use of the cell. When working at the lower intensities, a motor-driven sector disk was used between the cell and the magnesium carbonate block. This made it possible for observations to be made at a low brightness, with the energy level at the cell still sufficiently high for precise measurement.

The photo-cell used was one of the barrier-layer type, known as the "Electrocell," regular type, which has the advantage of having a higher sensitivity in the blue than most cells of this kind.

The position of the observer's head was fixed by means of a chin rest at about 11 inches from the comparison field. All the work was done without artificial aids to fixation.

Corrections

The method used here involved three principal sources of error which could be estimated:

(a) The slit width corrections were calculated for the entire spectral region used. Most of the work was done with slits 0.5 mm wide. The largest corrections found were approximately 0.5 percent. Since this is considerably less than the probable accuracy of the work, the corrections were not applied.

(b) The response of the cell, together with that of the galvanometer, was found to be not strictly linear. A calibration curve was therefore drawn for the combination and used to reduce all the observations.

(c) The block of magnesium carbonate, as applied in this work, was selective. It had a relatively lower reflectance for the blue than for the red wave-lengths. A correction curve was drawn, from data obtained on a goniophotometer, using filters for the isolation of narrow spectral bands. This correction was applied to all the observations.

Results and Comparisons with Other Work

Visibility at 6.5×10^{-5} foot lamberts

Fourteen observers were tested at 6.5×10^{-5} foot lamberts. Two of these were women and twelve were men. One of the men was known to be color-blind, according to tests made with the Ishihara charts. Although the nature of this observer's defect has not been studied critically, he appears to be a deuteranope of a not very uncommon type, and his data have been included in the general average. The curve shown in Fig. 2 represents the average result for all fourteen observers. The maximum occurs at 513 mμ.

The numerical values for the smoothed average curve are given in Table I.

Fig. 3 has the same smoothed curve with vertical lines added at intervals of 20 mμ to show the maximum and minimum values found for the fourteen observers. The points for the one color-blind observer and the average of the two women observers are also shown.

Louise Sloan[3] has written a comprehensive review of the results of various investigations of the visibility function, together with the results of her own observations under various conditions. Fig. 4 shows her results for a field of 4° 49′ diameter, a field illumination of 0.001 meter candle, and dark adaptation. The use of an artificial pupil in her apparatus made the effective intensity still lower. Although the experimental conditions are somewhat different, the curves are similar. Her curve shows a higher visibility in the red and a maximum a little lower, at about 500 mμ.

The logarithmic scale for relative visibility on these plots has been substituted for the arithmetical scale generally used, in order to show the positions of the lower points more fully.

Fig. 4a has been drawn using the same data used for Fig. 4. The departures of Sloan's data from the writer's average curve at points near the maximum seem to be unduly exaggerated, while the relative positions of the points near the red end of the spectrum are hardly discernible.

[3] Louise L. Sloan, "The Effect of Intensity of Light, State of Adaptation of the Eye, and Size of Photometric Field on the Visibility Curve," Psych. Monographs **38** (No. 1), (1928).

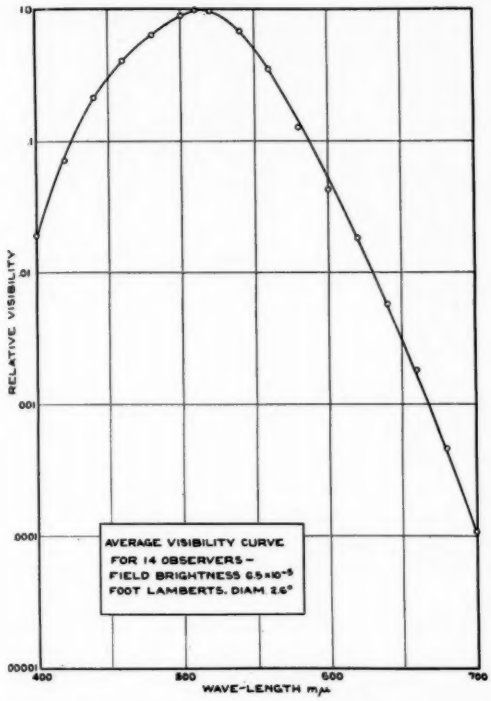

FIG. 2. Average curve for 14 observers taken at 6.5×10^{-5} foot lamberts, natural pupil, and binocular vision.

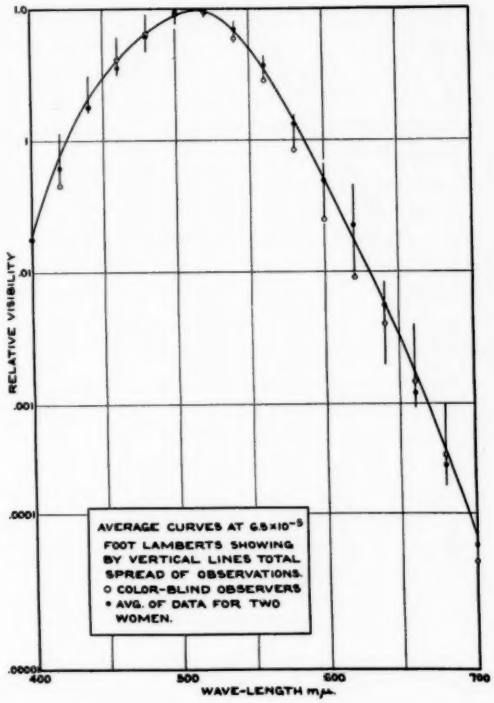

FIG. 3. Average curve compared with average data for the two women observers and the one color-blind (male) observer.

Fig. 5 shows a comparison with data of Laurens[4] using a two-degree field at an intensity of 0.2 meter candle reduced by the use of an artificial pupil. Laurens' maximum occurs at a wave-length of about 507 mμ.

Both Sloan and Laurens used monocular vision and an artificial pupil, whereas the writer used binocular vision and the natural pupils.

Hecht and Williams[5] made a set of measurements under conditions which are probably more nearly like those of the writer than any others available. They observed with binocular vision, natural pupils, and an intensity stated to be 2.7 times the dark-adapted threshold. This intensity was probably considerably below the value of 6.5×10^{-5} foot lamberts used in the present investigation. Nevertheless, in view of the fact that the maximum shifts but little in this intensity range, their results should be comparable with those of the writer. Fig. 6 shows the points given by Hecht and Williams in comparison with the average curve for those of the fourteen observers.

The comparison field was about 22 degrees, larger than the whole stimulus field in our apparatus, which was 14 degrees with the central

[4] H. Laurens, "Studies on the Relative Physiological Value of Spectral Lights. IV. The Visibility of Radiant Energy," Am. J. Physiol. **67**, 348 (1924).

[5] S. Hecht and R. E. Williams, "The Visibility of Monochromatic Radiation and the Absorption Spectrum of the Visual Purple," J. Gen. Physiol. **5**, 1 (1922–23).

TABLE I.

λ	V	λ	V	λ	V
400	0.0185	500	0.900	600	0.0490
410	.040	510	.985	610	.0300
420	.076	520	.960	620	.0175
430	.132	530	.840	630	.0100
440	.212	540	.680	640	.00575
450	.302	550	.500	650	.00315
460	.406	560	.350	660	.00170
470	.520	570	.228	670	.00087
480	.650	580	.140	680	.00044
490	.770	590	.083	690	.00021
				700	.000105

portion 2.6 degrees illuminated by monochromatic light.

These two curves are nearly alike. The curve for the fourteen observers is a little lower on both sides of the maximum, due possibly to the inclusion of a relatively large number of green-sensitive observers or to a slightly smaller effective field size, and the maximum at 513 mμ is a little higher than that of Hecht and Williams which occurs at about 510 mμ. This degree of agreement indicates that the size of the total stimulus field is as important as that of the area used in the comparison and that the specification of field size in itself is not significant unless the general form is also given. In the type of field used here, it is probable that the central portions of the retina are almost exclusively effective in determining the setting at high intensities, although the presence of the bright surrounding field does cause a reduction in the saturation of the monochromatic field. At the low intensities, the large total stimulus field helps to fixate the eye, permitting the measurements to be made for the central field, although the exact effective area may be uncertain. In fields having diametrical dividing lines, there is some question whether the size alone can greatly affect the measurements, except as it controls adaptation, as long as near central fixation is obtained.

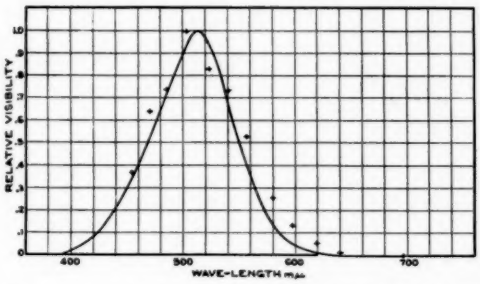

FIG. 4a. Average curve of the author compared with data of Sloan, plotted arithmetically.

The I.E.S. photopic curve is drawn as a dotted line in Fig. 6. It has been shifted bodily 42 mμ toward the blue end of the spectrum, making the

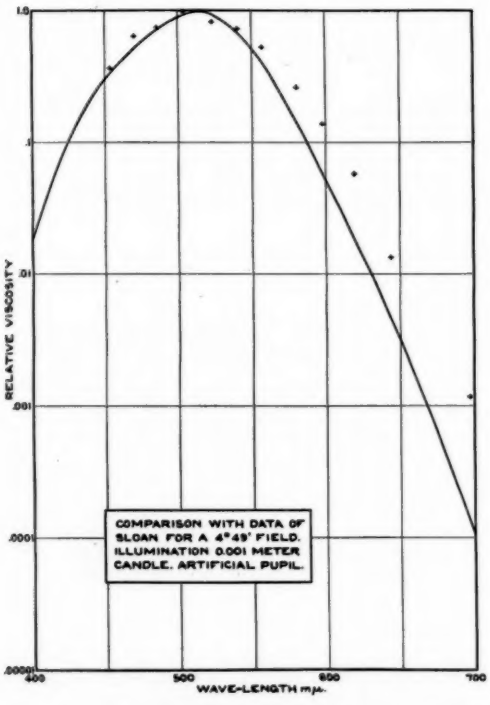

FIG. 4. Average curve of the author compared with data of Sloan for a low intensity.

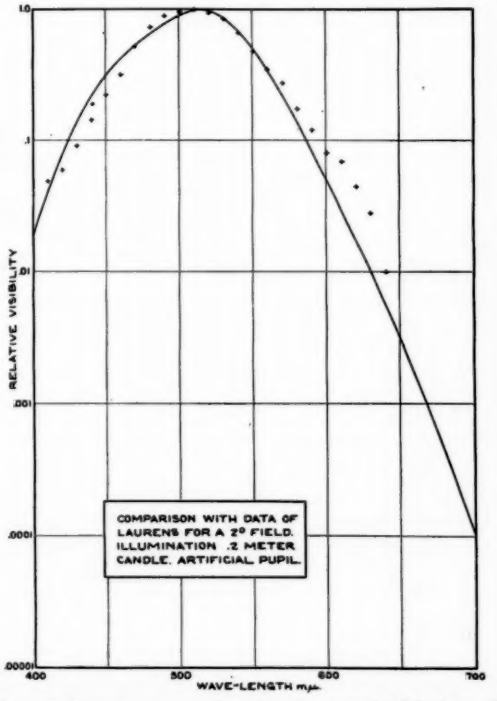

FIG. 5. Average curve of author compared with data of Laurens taken at a low intensity.

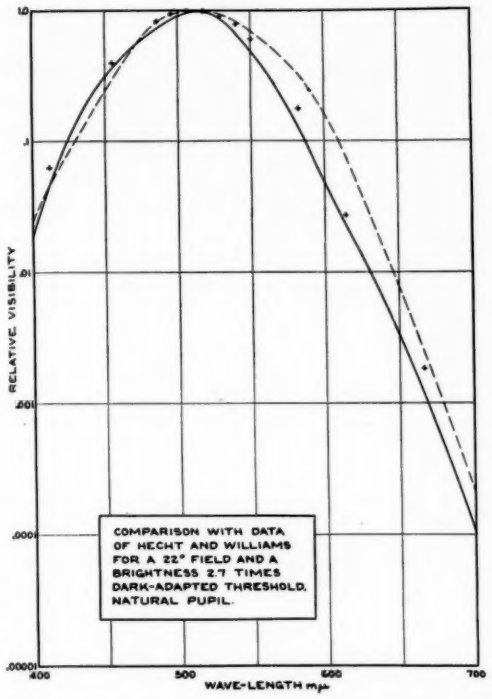

FIG. 6. Average curve of author compared with average data of Hecht and Williams based on 48 observers, binocular vision and natural pupil, and with the I.E.S. photopic curve shifted 42 mμ toward the left.

maxima coincide at 513 mμ. While these curves are similar in shape, there are differences larger than the probable experimental error in the determination of either of them.

Shift of maximum with intensity

For the investigation of the shift of the wave-length of maximum visibility with intensity, seven observers were used. Six of them were men included in the group of twelve used for the observations at 6.5×10^{-5} foot lamberts. All possessed normal vision.

In making these observations, a range of the spectrum was used just sufficient to define clearly the maximum.

In Fig. 7, the average result for the seven observers is shown as a solid line. Data from some observers gave curves differing considerably in shape from the average. Three showed fairly well-defined flat portions at high and low intensities; others did not. Most of the determinations came within plus or minus ten millimicrons of the average curve.

For comparison, there appears in Fig. 7 the dotted curve from König and revised by Nutting,[6] which was further adjusted for pupil diameter according to the curve of Fig. 8. The exact conditions under which König's data were taken are somewhat uncertain. He used an artificial pupil of constant size, and the lowest point corresponded to the threshold. Using these facts as a basis for estimate, the dotted curve of Fig. 7 was drawn. The correctness of the scale of intensities cannot be established definitely, but for a general comparison this is not essential.

In Fig. 7, one point corresponding to the result of the work of Hecht and Williams is placed at 510 mμ and at an intensity estimated to be equivalent to their specification of 2.7 times the dark-adapted threshold. The second lowest point on the writer's curve, which is at 6.5×10^{-5} foot lamberts, is the one at which complete data were taken on fourteen observers. The maximum for the seven observers is at 512 mμ, as compared with 513 mμ for all fourteen observers.

The standard I.E.S. visibility curve based on the work of Gibson and Tyndall has a maximum

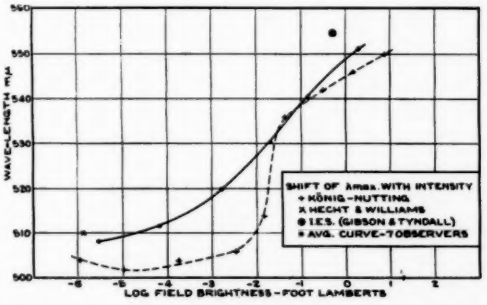

FIG. 7. Curve showing the shift of the wave-lengths of maximum sensitivity with field brightness with natural pupil. Data of König are shown dotted. This curve as modified by Nutting has been adjusted for pupil diameter, according to the approximate (one-observer) curve of Fig. 8. The exact position of his intensity scale as well as the total extent is not certain. The position of the maximum according to Hecht and Williams for an intensity 2.7 times the dark-adapted threshold, and the maximum for the I.E.S. photopic curve have been inserted for comparison.

[6] P. G. Nutting, "The Visibility of Radiation: A Recalculation of König's Data," Bull. Nat. Bur. Standards **7**, 235 (1910); R. A. Houstoun, *Vision and Color Vision* (Longmans, Green & Co., 1932), p. 86.

at 555 mμ. The maximum field brightness used by Gibson and Tyndall was about 49 foot lamberts (53 millilamberts) equivalent, when allowance is made for the exit slit area, to 12 foot lamberts through a pupil of 1 sq. mm, or about 40 photons. Allowance for the size of the natural pupil reduces this brightness to about 0.5 foot lambert (Fig. 7). The standard photopic curve is based on a rather low retinal illumination.

For this value of field brightness, the maximum, from the author's curve, is 546 mμ, a value about 9 mμ lower than the I.E.S. curve. Although this difference seems greater than would be expected, it may be due partly to the limited number of observers used by the author, as well as to the difference in the field and the conditions of vision.

At the higher intensities, no well-defined shoulder is found either in König's curve or in the author's own average curve. The curves of certain observers did show a more pronounced shoulder than the average, but there seems to be no region of intensities wherein the visibility curve ceases to change. Location of the position of the maximum is of course not sufficient to define the visibility curve at a particular level of brightness; it is only indicative of a general trend.

Sloan[8] has found that, for her eye, significant changes in shape occur, not only from change of intensity, but also from other variables. "No experimental condition has been found in this study under which the eye is entirely free from the selectiveness of response to intensity."

The problem of photometry over a wide intensity range

Although experience has shown that the present standard photopic curve serves very well for photometric calculation in most problems of photopic vision, there are frequent cases where the intensity effect seems to appear rather unexpectedly with moderately low intensities. Holst, Geise and Zwikker[7] describe an investigation of errors as high as 5 percent found in a comparison of the Hüfner standard lamp with vacuum lamps at different color temperatures.

[7] "L'Exactitude de la Photometrie," Appendix I, Proc. Int. Ill. Cong. **1**, 110 (1931).

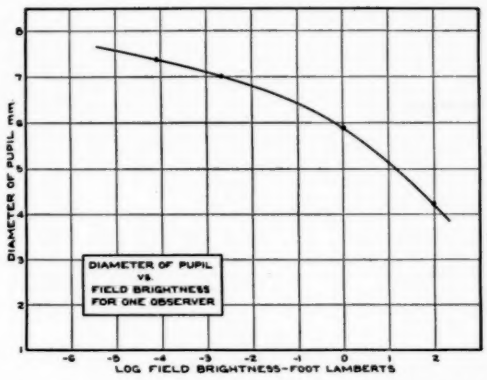

FIG. 8. Relation between the pupil diameter and field brightness for a 14° circular field, after complete adaptation at each level.

They conclude that in cases where the Hüfner lamp is used with a correcting filter and a low intensity on the photometer screen, the photopic visibility curve should not be used for the calculation of the transmission of the filter.

The outstanding problem in photometry at low levels, aside from that of a more complete statistical determination of the visibility function, is one of definition of the energy distribution used in specifying the intensity scale. In the present work the intensity scale is defined as that given by a source having a color temperature of about 2500°K, photometered at an intensity of about one foot lambert and reduced by the use of neutral filters. Had a monochromatic red or blue radiation been used as a source to establish the intensity scale, an appreciably different intensity scale would have resulted. This relation was shown by Abney[8] in his early investigations.

The selection of a suitable energy distribution for this purpose is a matter for international standardization. Its need has been generally recognized for some time[9] but, since in most photometric work fairly high field brightness is obtainable, the need has not been as urgent as the need for a standardized photopic visibility curve. Just what energy distribution is selected

[8] W. Abney, *Researches in Color Vision* (Longmans, Green and Co., 1913), graph on p. 101.

[9] P. G. Nutting, "The Luminous Equivalent of Radiation," Bull. Nat. Bur. Standards **5**, 299 (1908–09) (paragraph 17).

is not so very important as long as it is easily defined and readily produced experimentally. A monochromatic radiation might be used although, in the opinion of the author, a blackbody distribution readily obtainable with a tungsten lamp would be most convenient. Other factors than that of experimental convenience might indicate that a distribution such as sunlight, daylight, or one of the illuminants adopted as standard for colorimetry by the I.C.I. would be preferable. The effect of the choice of an energy distribution on the openness or compactness of the luminous scale does not seem very important, as long as monochromatic red or blue radiation is avoided.

We also have need to clarify or amplify our notation in the designation of light flux. Radiant energies of two different wave-lengths, of the same luminous value at a high intensity, when acted upon by the same neutral absorbing device (sector disk, neutral filter, or inverse square law), will no longer have the same luminous value, although they represent equals divided by the same thing. The significant fact, of course, is that a nonselective absorber for energy is selective for luminosity, due to the nature of the response of the eye, and that for a unique specification of intensities at all levels, further definition is needed.

Summary

A visibility curve based on data from fourteen observers was taken at an intensity of 6.5×10^{-5} foot lamberts.

(*a*) The curves of several other investigations taken at comparable intensities are in substantial agreement as to shape and position of the wave-length of maximum sensitivity.

(*b*) Considering all the available data, the curve for the lower level is probably sufficiently well defined for practical purposes.

(*c*) A curve indicating the shift of the wave-length of maximum sensitivity with intensity for seven observers is given and comparison made with the similar curve of König.

(*d*) This curve is thought to be indicative of the general form of this function, although a larger number of observers are needed to obtain a statistically representative curve.

(*e*) A source of ambiguity in the present conception of the intensity scale is pointed out and a suggestion made that some energy distribution be standardized as a basis for the intensity scale.

The author wishes to acknowledge his indebtedness to Dr. J. H. Webb, who calibrated the photo-cell used in the work; to Dr. L. A. Jones and Mr. E. M. Lowry, who made suggestions used in carrying out the investigation; to Mr. H. E. Hussong, who conducted most of the tests; and to members of the laboratory who acted as observers.

Optics and the Textile Industry*

EDWARD R. SCHWARZ
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received November 11, 1936)

IT is only natural that an industry whose products depend to so large an extent upon pleasing appearance for successful sale should turn to the science of optics to aid in studying and perfecting fiber, yarn and fabric. Optical instruments ranging from the simple magnifying lens to the polarizing microscope; from the Duboscq colorimeter to the automatic spectrophotometric color analyzer; from the celluloid diffraction yarn counter to the x-ray diffraction camera, are finding constantly increasing and important uses in the hands of textile technologist and manufacturer alike. All the way from the analysis of the ultimate structure of the long chain molecules of cellulose, fibroin, and keratin by means of x-ray diffraction patterns through the determination of the fibrillar structure of fibers by means of the polarizing microscope, to the quantitative evaluation of fabric properties by means of the binocular stereoscopic microscope, optics plays a vital part.

In the past the chemist has pioneered in textile research and has laid a most valuable foundation. Now his work must be extended and clarified by the physicist. A most important problem confronting the investigator in the field of textile physics is that of the properties of the fibers which are used in the manufacture of yarn and fabric. As a chain is no stronger than its weakest link, so a fabric is no better than the fiber it contains. And the properties of the fiber can only be studied intelligently in the light of complete knowledge of the minutest details of structure. Hence the emphasis upon microscopic analysis, since it becomes immediately necessary to cut infinitesimally thin slices from nearly invisible filaments, and further to dissect these slices to lay bare the secrets sealed there by nature or the test tube.

In botanical technique, in electronics, in colloid chemistry, in x-ray spectrography, in color photography, in high speed photography, in fluorescence analysis, in all the many fields of physics and physical chemistry, each new discovery is a potential weapon in the attack upon the unsolved problems of the textile industry. Dr. Bush of Massachusetts Institute of Technology writing in a book[1] published by the United States Institute for Textile Research, said, "Considering the fact that he has been at it for only a few thousand years, man makes rather good textiles. Compared to nature, however, he is still an amateur with much to learn. . . . It is just as necessary for the modern executive to understand the examination of fibers under polarized light as to know the mechanics of a spinning frame or to be able to read a balance sheet. Of course he cannot hope to know all the underlying optics, any more than he would attempt to operate personally any or all of the machines in his plants, or keep up with all the intricacies of present-day cost accounting systems; but he can understand those things which are important to his business and this is now one of them. . . . There is no field in which there is greater opportunity for accomplishment than that of textiles." Dr. Bush is in a position to know of what he speaks, and in the light of his clear and forceful statement the young industrial physicist may well consider the opportunities which are opening up in a well-nigh virgin field. Such a man need never despair of there being no new worlds to conquer, and with the importance of the physicist (particularly if he has a thorough training in optics) being increasingly recognized by the industry, the years ahead should indeed prove fruitful—fruitful not only to the men to take up the practice of textile technology, but for the industry which they serve by reason of the new developments and important contributions to the present store of knowledge which they can and will bring about.

* Read by invitation at the meeting of the Optical Society of America held at New York, October 30 and 31, 1936.

† Associate Professor of Textile Engineering, in charge of Textile Research, M.I.T.

[1] *Textile Research: A Survey of Progress* (M.I.T. Press).

FIG. 1. Ramie fiber in polarized light.

As in other fields, pure scientific research is the fountain-head from which wells up a continual supply of facts, of explanation, of inspiration, to keep alive the industrial application of fundamental principles. Of the many examples, only one need be cited here. Early in the experience of the writer as a textile technologist it became apparent that since all textile fibers were excellent polarizers of light—many of them ten times as doubly refractive as quartz—it was only reasonable to study them by means of polarized light. The aid of petrographers and chemical microscopists was sought to develop the necessary equipment and technique. The willing cooperation of colleagues from both fields made possible a research program which had no practical industrial application as a goal. It was research undertaken for its own sake—but not for long. Out of it grew immediately the knowledge that here was a means for quickly and cheaply grading cotton fiber for maturity. Mature, thick-walled, tough, and strong fibers produce the most uniform yarn, free from troublesome uncontrolled surface fibers and undesirable bunches of immature fiber—the neps which are the bane of many a cotton manufacturer's existence. Under proper conditions of examination in elliptically polarized light cotton fibers of varying maturity appear in distinctly different colors. In not many more minutes than it takes to tell it, a bale of cotton can be sampled and its maturity rating computed with a polarizing microscope equipped with a first-order selenite. A cotton classer's microscope will soon be placed upon the market at a price—because of economies affected by the use of one of the newer polarizing materials—which places it well within the means of the average mill laboratory. A number of mills are already using the technique with satisfaction. Such developments as this are giving point to the slogan of the textile investigator using optical instruments—"Why guess when you can see?"

It has been a privilege for the staff of the M.I.T. Textile Laboratory to have a part in dispelling the fear and distrust of optical equipment prevalent in the past in the textile industry of this country both by education and example as has been done in England by Preston and Astbury and in Germany by Alois Herzog. There is an increasing literature on the subject with the publication of such books as *Modern Textile Microscopy*, *Mikroskopische und mechanisch-technische Textiluntersuchungen*, *Textiles and the Microscope*, *Fundamentals of Fiber Structure*, and *Die textilmikroskopischen Untersuchungen in der Praxis*, together with hundreds of worthwhile papers in the leading textile journals and frequently of late in the journals of applied physics and chemistry.

Ignorance of the part which optical equipment might play in aiding textiles has been largely responsible for the hesitancy about its adoption. But courses of instruction, publications, and above all, the results of application have convinced more and more textile manufacturers that textile research, whether for product development, elimination of difficulties of manufacture, or determination of basic information as to raw materials is incomplete without optics.

Fabrics are made up of yarns. Hence the analysis of fabric structure is concerned qualitatively with the surface appearance of the material and with the interlacing of yarns with each other. Sleight-of-hand experts to the contrary notwithstanding—it is not possible for two yarns to occupy the same space at the same time. They must cross above and below each other, in both directions of the fabric. Consequently all fabrics are three dimensional. Many desirable cloths are produced by accentuating this third dimension as in velvets, plushes, carpets, terry towels, lappets, swivels, honey-

combs, lenos, laces and knit goods. The stereoscopic binocular microscope is essential for examinations of this kind.

Fabric analysis may be quantitative. For example, the number of yarns per inch and the variation in this count can be determined by means of pick counters, variably spaced diffraction gratings ruled on glass or celluloid and by measurement of the fabric cross section. From the latter aspect of the fabric it is also easily possible to measure thickness, yarn shape, covering power, porosity, waviness or crimp and weave in a rather short time. Several of these measurements, if made by the usual mechanical methods, would consume up to ten times as long.

The yarns themselves are made up of fibers or filaments held together by means of twist. The optical analysis of twist is being steadily improved to provide convenient means for determining not only turns per inch, but variation in helix angles and yarn diameter, twist and ply contraction and the compactness of the structure. The technique allows for examination of the specimen at closely or widely spaced intervals and does not alter the yarn as do the older methods of mechanical testing.

But if optical equipment and technique are important for many forms of fabric and yarn analysis, they are infinitely more so for the study of fibers. The vast majority of commercial textile fibers are only a few microns in diameter and are of complex internal structure. For many years workers all over the world have used the microscope to study fibers, but only comparatively recently has serious effort been made to correlate the work with the progress in chemistry and physics.

In 1665 a paper was presented in England to the Royal Society by Dr. Hooke and later the findings were included in a book on hair and wool structure entitled *Micrographia of Some Physiological Descriptions of Minute Bodies Made by Magnifying Glasses with Observations and Inquiries Thereon.* To quote from this volume:

"Of the Figure of several sorts of Hair, and of the texture of the skin.—Viewing some of the Hairs of my Head with a very good Microscope, I took notice of these particulars:—

"(1) That they were, for the most part, Cylindrical, some of them were somewhat Prismatical, but generally they were very neer round, such as are represented in the second Figure of the 5 scheme, by the cylinders *EEE* nor could I find any that had sharp angles.

"(2) That the part which was next the top, was bigger than that which was nearer the root.

"(3) That they were all along from end to end transparent, though not very cleer, the end next the root appearing like a black transparent piece of Horn, and next the top more brown, somewhat like transparent Horn."

FIG. 2. Half of a stereogram of honeycomb weave. In many fabrics the third dimension can best be shown by this form of microanalysis.

The science of finger printing for the identification of human beings is wide spread and widely accepted as a powerful weapon in the war on crime. It is interesting to note that a startlingly similar technique is now being used, among other things, for the study and identification of fibers and fabrics. A celluloid impression can easily be taken of a fiber surface to register very clearly the physical structure such as scales, fissures, and roughness, which would otherwise (often because of natural or artificial coloration) be extremely hard to detect. Such impressions must be examined with a microscope and make possible the study of fiber distortion with direct correlation with physical tests. It may be a far cry from Dr. Hooke's investigation of human hair to the study of hair impressions by Hotte[2] as an aid to meteorological research, but they were

[2] G. H. Hotte, *Microanalysis of Human Hair*, M.I.T. Meteorological Course, professional notes, No. 8, June (1935).

FIG. 3. Photomicrograph of celluloid impression of the surface of a human hair (G. H. Hotte).

FIG. 4. Fibrillar structure of the cotton fiber in polarized light.

none the less brothers under the skin. To continue briefly with the quotation from Dr. Hooke's notes:

"(4) That the root of the Hairs were pretty smooth, tapering inwards, almost like a Parsneb; nor could I find that it Had any filaments, or any other vessels, such as the fibers of Plants.

"(5) That the top when split (which is common in long Hair) appe'red like the end of a stick, beaten till it all be flitter'd, there being not onely two splinters but sometimes half a score more.

"(6) That they all, as farr as I was able to find, were solid cylindrical bodies, not pervious, like a Cane or a Bulrush; nor could I find that they had any Pith, or distinction of Rind, or the like, such as I had observ'd in the Horse-hairs, the Bristles of a Cat, the Indian Deer's Hair, etc.

"Observation on several other sorts of Hair.—Bristles of a Hogg. Mustacheos of a Cat. . . . the long hairs of Horse *CC* and *D*, seem cylindrical and somewhat pithy; the Bristles of a Cat *B*, are conical and pithy: the Quils of Porcupines and Hedghoggs, being cut transversely, have a whitish pith, in the manner of a Starr, or Spur-rowel: Piggs-hair (*A*) is somewhat triagonal, and seems to have neither pith nor pore: And other kinds of hair have quite a different structure and form.

"Dyed hair appear'd quite throughout tinged with the colours they exhibited. . . . the ting'd parts come to be mixed and united with the very body of the hair, and do not (as some have thought) only stick on upon the outward surface." The mechanism of dyeing still presents an unsolved problem, toward the solution of which optics will make no small contribution.

The transition from qualitative to quantitative studies was gradual and is noted in a series of papers by Anderson (1776), Daubenton (1777–1784), Ploucquet (1785), Parry (1806), Andre (1819), Young (1824), Nathusius (1866–1880), Matthews (1916), and many notable contributions to the literature in 1922 and throughout the last 14 years.

Now not content with qualitative examination the quantitative grading of wool tops for quality has become an everyday affair. A special projection microscope and use of the wedge measuring system obviates the necessity for complicated sampling and mounting technique and avoids the difficulty and fatigue of making large numbers of scale readings. The resulting "wedge diagram" is the basis for a simply worked up frequency array which allows rapid computation of the average fiber fineness, the percentage of fibers above and below certain limits and the precision of the mean. Research now being conducted by the Textile Foundation with the cooperation of the American Society for Testing Materials, the National Association of Wool Manufacturers and the United States Department of Agriculture is the logical basis for establishment of new standards for this country which will be in close accord with the usages

abroad, and which will be more generally practical for use by the manufacturer than the present system.

While it is true that wool like all other textile fibers is doubly refractive, it has a lower specific index of birefringence than does cotton and up to the present, at least, little work has been done with wool in polarized light. On the contrary cotton has been studied rather intensively by this means by Osborne working under a Textile Foundation Fellowship with the author. The wall of the cotton fiber is composed of many layers of cellulose laid down successively during the latter stages of the fiber's growth. The long-chain molecules, grouped into fibrils, are formed at an angle with the longitudinal axis of the fiber, and since they show substantially parallel extinction between crossed Nicols, a series of optical sections can be taken on a longitudinal mount of a slightly swollen fiber to demonstrate conclusively that the fibrils do not cross each other in adjacent layers, as was held by some previous investigators who did not have the advantage of working with a polarizing microscope. Not only can the fibril (and something of the molecular) orientation be studied, but it is found that for cotton, as for many other natural and synthetic fibers, details of structure are more clearly displayed for examination and photography than by ordinary methods of illumination. Time does not permit a review of Osborne's work nor of the work of other investigators in the field of cotton fiber structure. It should be mentioned, however, that a substantial portion of the interesting findings of Mrs. Farr and her co-workers at the Boyce-Thompson Institute were made easier by use of polarized light. Practical results have likewise come from the research undertaken at M.I.T. The very simple method for grading cotton maturity (development of the secondary wall of the fiber) as already mentioned has been worked out and is being adopted by an increasing number of mills and laboratories.

In brief, the primary wall (and cuticle) of the cotton fiber show practically parallel extinction, whereas the spiral structure of the secondary cellulose deposit because of gradual change of the angle of inclination as the fiber axis is approached shows only very localized and imperfect parallel extinction. Thus, immature fibers, which have little or no secondary deposit appear a deep purple in the 45° additive position between crossed Nicols and with a first-order selenite. Partially immature fibers (with only a very slight secondary deposit), because of their thickness, show a clear blue throughout their entire visible length in the field of a 16-mm objective. Partially mature fibers appear either alternately blue and yellow, or greenish, while mature fibers are clear yellow. Upon rotation of the fiber to the subtractive position, the immature fibers appear deep orange, the partially immature fibers appear deep yellow, the partially mature fibers a lighter yellow, while the mature fibers remain unchanged. By means of a simple counting device it is easily possible for the classer to measure several hundred fibers in a matter of less than ten minutes, and obtain a maturity rating by properly weighting the percent of each class of fiber found. The determination of the proper weighting coefficients is a matter for investigation under the particular conditions of manufacture or otherwise which exist at the time. Progress is being made in this direction. Again optical analysis has made possible rapid and precise quantitative determinations instead of the unsatisfactory guess or estimation of the usual examination. Since the presence of immature fibers substantially weakens the resulting yarns, interferes with their proper dyeing, produces a fabric impossible to emboss by Schreinering and gives a fuzzy rather than a smooth yarn, the elimination of lots of cotton containing more than an acceptable minimum of immature fiber is an important matter. Once

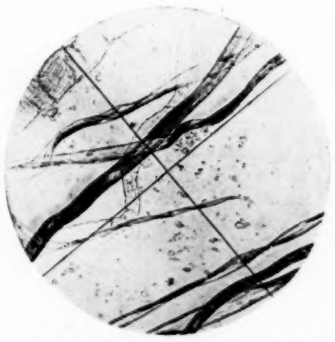

FIG. 5. Cotton fibers in polarized light.

the immature cotton gets into the plant it is impossible to do anything about it.

It is unnecessary to do more than mention in passing the work in spectrophotometric color analysis carried out by such well-known workers in the field of optics as D. B. Judd and A. C. Hardy. The importance of convenient, complete and precise data for color specification, matching and measurement to the textile industry is at once evident. Much more may now be learned regarding the mechanism of fading, the mechanism of dyeing itself, and much progress is bound to be made in the direction of simplification resulting from better control of dyes used to produce a desired shade.

And with the mention of dyes, attention should be directed to investigations underway in this country and abroad in the field of pleochroic dyes. Not only will studies of fibers so colored be of academic interest, but they bid fair to aid in the attack on the vast no-man's-land of fiber structure detail too small for direct micro-observation, and too large for x-ray diffraction analysis. By noting that certain dye molecules are lined up with the molecular structure of the fiber, and measuring the variation in the vibration directions of the polarized fluorescence produced in ultraviolet radiation, Morey in this country and Preston in England have opened up a fruitful field for future work.

It is not beyond the realm of possibility that a technique for stress analysis, in synthetic fibers at least, by a modified photoelastic method may be successful. It has already been demonstrated by work in progress in the M.I.T. textile microscopy laboratory that a photometric measurement of stress intensity is possible for such materials, as well as for determining quantitative changes of certain swelling forces in cotton.

The petrographer is accustomed to identifying minerals included in a thin slice of rock by means of the characteristic colors produced in polarized light because of differences in their specific indices of birefringence. The reverse of this technique is used to study variations in thickness in fibers of substantially constant specific index, or to determine the specific index when the cross section can be measured. A convenient device for contour measurements in rayon is the biquartz compensator set at 45°

FIG. 6. Single filament of nitrate rayon showing the contour diagram and retardation scale as produced by the special petrographic microscope.

with the planes of polarization and used in conjunction with a positive eyepiece on a petrographic microscope. The retardation can thus be read directly and can be properly combined mathematically with either a known specific index to determine the filament thickness at that point or with a known thickness to determine the specific index. The latter technique frequently can be employed with considerable saving of time as compared with even the Emmons double variation immersion technique. The double variation method, however, is of value where the magnitudes of the maximum and minimum indices of refraction are required—as

for orientation measurements. Interesting developments are likely to be forthcoming as a result of such investigations.

The recording of the early stages and the further progress of fiber swelling and disintegration by means of the moving picture camera in conjunction with the microscope has already been started. Use of the Edgerton high speed motion picture camera in this work is the next logical step. Improvement in equipment and technique worked out by Edgerton, together with improvements underway in handling the fibers to be studied are likely to make visible changes which are of considerable importance from both theoretical and practical considerations and which up to the present have been impossible to see, much less to time.

The method of stroboscopic photography for the study of rapidly moving objects can also be applied effectively to textiles. It is possible, for instance, to obtain pictures showing any desired instantaneous position of an object such as the ring traveler on a spinning frame moving say 9000 revolutions per minute. The pictures are sufficiently sharp so that even projecting fibers on the ballooning yarn are sharply defined. The technique makes possible improved design of moving parts and also direct study empirically of the variations in yarn tension during the spinning operation, precise timing of loom mechanisms, etc. At least one commercial model of circular knitting machine has a stroboscopic attachment built into the machine for the purpose of more precisely controlling the feeding of several yarns.

Since the surface properties of textile fibers are responsible in no small measure for the excellence or inferiority of the resulting yarn, their measurement and classification is of importance to the textile industry. Little satisfactory work has been done in this field as yet because of the difficulty in making the surface conditions which exist clearly visible. Because of the relatively high absorption of incident light by textile fibers as compared with metals, the usual vertical illuminator is unsuited to textile work. The advent of the so-called Ultropak or Epi-condenser systems of illumination for powers of the microscope up to and including the highest oil immersion now makes studies of fiber surfaces easier. Much work must be done along this line. Such systems of illumination (at the lower powers) are also very well suited to examination of yarns and fabrics where, because of the opacity of the specimen (naturally or by reason of finishes or coatings), transmitted light is of no use.

Direct color photomicography for both still and motion pictures is easily possible and has been used with great satisfaction particularly to record colors produced in polarized light. Such pictures have already appeared in the literature[3] and will appear more frequently in the future.

Although only a few of the important contributions of optics to the textile industry in the field of research and control have been mentioned, it should be apparent that the importance of the science cannot be overestimated. The research worker with training in this field will find before him a nearly virgin territory. I have no hesitation in predicting that optics will both literally and figuratively throw an increasing flood of light upon the many dark portions of textile technology. The work has just begun. Opportunities for worthwhile contributions are appearing upon every hand. The physicist will do well to think seriously of applying himself to work in a field which the textile industry is increasingly considering of vital importance.

[3] Textile World, July (1935), p. 89.

A Biprism for Use in Stellar Interferometry

EDWARD M. THORNDIKE
Polytechnic Institute of Brooklyn, Brooklyn, New York
(Received November 11, 1936)

It is shown that a biprism producing deviations proportional to the wave-length will be of value in stellar interferometry. The design, construction, and testing of an instrument employing such a biprism made of crown and flint glasses is described.

INTRODUCTION

IT is well known that the resolving power of a telescope can be increased by covering all of the objective except two slits at opposite ends of a diameter. This arrangement, with slight modification, has been used by several observers to measure the separations of binary stars and also, with more extensive changes, to measure the diameters of a few stars. The aim of this report is to discuss certain changes which can be made to improve the usual apparatus.

The light coming to a telescope from a celestial body will not be monochromatic but will have all wave-lengths in the visible range, and further it will not come in a single direction but in all directions within a cone which the source subtends at the telescope. First, consider light of all wave-lengths to come from a single point of the source, and suppose a pair of parallel slits of equal width, with their center lines separated by a distance l, to be placed in front of the objective of a telescope of focal length f. Taking λ as the wave-length of a representative wave train, its interference fringes produced in the focal plane of the telescope will have a width b given by the equation

$$b=\lambda/\alpha=\lambda f/l, \tag{1}$$

where α is the angle between the recombining rays which in this case is l/f. Since f and l are constants in a given arrangement, b is proportional to λ. It is evident that with white light the interference patterns from different wave-lengths can only coincide along one particular line, the central bright fringe. This makes the composite pattern slightly indistinct near the center and completely obliterated farther from the center. The white-light fringes near the center of the pattern will have a width $b=\lambda_e f/l$ where λ_e is the "effective wave-length"[1] of the white light.

Next, consider light of one wave-length coming from the entire source. While the general case of a source having any distribution of intensity over its surface has been treated by Michelson,[2] it will suffice for this discussion to consider the simpler case of two point sources. The interference pattern formed by monochromatic light from one of the points will have the same fringe-width as that formed by the other point, namely $b=\lambda f/l$, but one pattern will be displaced relative to the other. If the two point sources subtend an angle ϕ at the telescope, the patterns will be displaced by a distance ϕf or $(\phi l/\lambda)b$. If $\phi l/\lambda=\frac{1}{2}$, the maxima of intensity in one pattern will fall on the minima of the other and the composite pattern will show the least variation in intensity. In measuring the angular separation ϕ of the point sources, l is adjusted until the fringes are least distinct, and then

$$\phi=\lambda/2l. \tag{2}$$

The smallest angle that can be measured in this way depends upon the maximum value that l can assume (the aperture of the telescope objective), and depends also upon the wave-length of the light from the source.

In stellar measurements the point sources will not be monochromatic nor will they have exactly the same wave-length distribution of intensity. In order to calculate their separation from the distance between the slits which gives minimum distinctness of pattern; one must again use an "effective wave-length."

An arrangement for giving a pair of slits a

[1] The exact meaning of "effective wave-length" and methods of determining it are discussed fully by J. A. Anderson, Astrophys. J. **51**, 263 (1920).
[2] A. A. Michelson, *Studies in Optics* (University of Chicago Press), Chapter XI.

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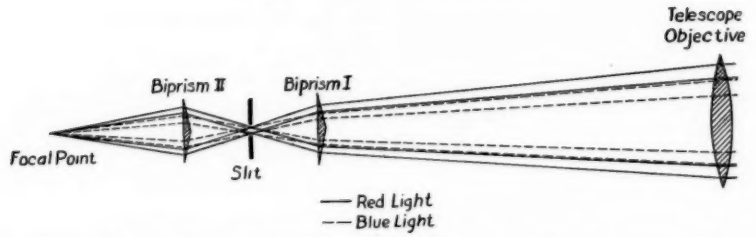

FIG. 1. Two biprisms and a slit arranged to give effective slits at the telescope objective with separations proportional to the wave-length. Both biprisms are intended to give deviations proportional to the wave-length, biprism II giving twice the deviation of biprism I.

separation that is proportional to λ would possess a number of advantages over the use of a fixed pair of slits. In the first place, the fringe-width, which depends upon λ/l, would be rendered independent of the wave-length. Secondly, it would be unnecessary to assign an "effective wave-length" in the determination of the separation of a double star or the diameter of a celestial body, since these also depend upon λ/l. In the third place, the resolving power of the telescope could be increased somewhat by using only the light of shorter wave-lengths.

Fig. 1 shows an arrangement using biprisms for achieving this end. If the biprisms produce deviations which are proportional to the wave-lengths, it is evident that the light of different wave-lengths which reaches the focus after passing through the slit will have come through regions of the objective whose separations are proportional to the wave-lengths. The particular part of the objective through which light comes to this focus can be altered by moving the slit toward or away from the objective. In Fig. 1, the relative positions of the biprisms and the focal plane are such that the biprism II must produce twice the deviation given by biprism I. Fig. 2 shows a modification in which the two biprisms produce the same deviation. This arrangement can be changed slightly so that only one biprism is necessary. The incoming light is made to pass through its lower half (acting as biprism I) to a right angle prism which directs it up to a second right angle prism which sends it through the slit and back through the upper half of the biprism (acting as biprism II). This was the arrangement used. Both of the arrangements require biprisms which will produce deviations which are as nearly proportional to the wave-length as possible.

DESIGN AND CONSTRUCTION OF THE BIPRISM

To design a biprism to yield deviations proportional to wave-length, consider plane parallel light of three wave-lengths λ_1, λ_2 and λ_3, incident upon the biprism shown in Fig. 3. The biprism with angle θ is made of crown glass having indices of refraction denoted by values of μ appropriately subscripted for the wave-lengths mentioned; similarly the biprism with angle θ' is made of flint glass having refractive indices

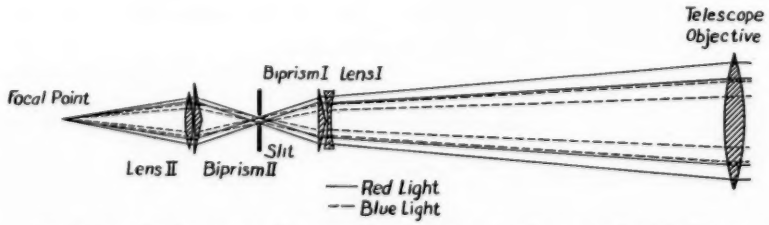

FIG. 2. Two biprisms and a slit arranged to give effective slits at the telescope objective with separations proportional to the wave-length. Both biprisms are designed to give deviations proportional to the wave-length. Biprisms I and II are identical. Lens I furnishes parallel light while lens II brings the light to a focus.

FIG. 3. A biprism built of one crown and two flint prisms. The angles θ and θ' are chosen to give interference fringes of equal width for the C and F lines.

denoted by primed values of μ. Let b_1, b_2 and b_3 represent the widths of the interference fringes for light of wave-lengths λ_1, λ_2 and λ_3 and assume θ and θ' to be small. Applying the equation for the deviation produced by a small angled prism to Eq. (1) gives—

$$b_1=\lambda_1/2[(\mu_1-1)\theta-(\mu_1'-1)\theta'],$$

$$b_2=\lambda_2/2[(\mu_2-1)\theta-(\mu_2'-1)\theta'],$$

$$b_3=\lambda_3/2[(\mu_3-1)\theta-(\mu_3'-1)\theta'].$$

These equations will be simplified if $\mu-1$ is replaced by a single symbol, say δ. Thus

$$b_1=\lambda_1/2(\delta_1\theta-\delta_1'\theta'), \tag{3}$$

$$b_2=\lambda_2/2(\delta_2\theta-\delta_2'\theta'), \tag{4}$$

$$b_3=\lambda_3/2(\delta_3\theta-\delta_3'\theta'). \tag{5}$$

In general it will be impossible to make $b_1=b_2=b_3=b$, where b is the desired common fringe-width, because θ and θ' are the only quantities which can be adjusted. However, it is possible to make $b_1=b_3=b$ and to determine the conditions which the values of μ or δ must satisfy to make b_2 also equal b. To proceed in this manner, first solve Eqs. (3) and (5) for θ and θ', taking $b_1=b_3=b$. One obtains—

$$\theta=\frac{\lambda_1\delta_3'-\lambda_3\delta_1'}{2b[\delta_1\delta_3'-\delta_1'\delta_3]}, \tag{6}$$

$$\theta'=\frac{\lambda_1\delta_3-\lambda_3\delta_1}{2b[\delta_1\delta_3'-\delta_1'\delta_3]}. \tag{7}$$

Substitution of these values in Eq. (4) yields—

$$b_2=\frac{b\lambda_2(\delta_1\delta_3'-\delta_1'\delta_3)}{\lambda_1(\delta_2\delta_3'-\delta_2'\delta_3)+\lambda_3(\delta_1\delta_2'-\delta_1'\delta_2)},$$

from which it is evident that $b_2=b$ when—

$$\lambda_2(\delta_1\delta_3'-\delta_1'\delta_3)=\lambda_1(\delta_2\delta_3'-\delta_2'\delta_3)+\lambda_3(\delta_1\delta_2'-\delta_1'\delta_2). \tag{8}$$

All the development thus far is based upon the assumption of small prism angles. Substitution of numerical values in Eqs. (6) and (7) shows that these can only be realized if care is exercised in keeping $\delta_1\delta_3'-\delta_1'\delta_3$ reasonably large. This requires that δ_1/δ_3 and δ_1'/δ_3' be as unequal as practicable. It would be surprising indeed if a pair of glasses satisfying this requirement and that imposed by Eq. (8) could be found. Fortunately pairs of glasses yielding reasonably small prism angles can be found such that when the biprism angles are chosen to make the fringe-width the same for the C and F lines, the fringe-widths for all intermediate wave-lengths will differ from this value by only a few percent.

The glasses used had refractive indices as given below:

Wave-length	Crown	Flint
6563 (C)	1.50943	1.74528
5893 (D)	1.5118	1.7532
4861 (F)	1.51747	1.77271

For $b_C=b_F=b=5\times10^{-3}$ cm, Eqs. (6) and (7) give for these glasses $\theta=10°\ 24'$ and $\theta'=6°\ 36'$. A slight correction, arising from the fact that these angles are not quite small enough to use the simple deviation expression, has been made. It requires that θ be changed from $10°\ 24'$ to $10°\ 26'$, θ' being unchanged. Using these angles and a rigorous expression for the deviation produced by a prism the following fringe-widths are obtained:

Wave-length	Fringe-width
6563 (C)	5.0×10^{-3} cm
5893 (D)	4.8 "
4861 (F)	5.0 "

This slight variation in fringe-width did not introduce any observational difficulties.

In assembling the biprism, the two flint prisms must be placed on the crown prism so that the lines b and c are parallel to and equidistant from the edge a. These adjustments were made, after the parts had been cemented, by heating them to a temperature of about 90°C in order to soften the cement and then sliding the flint prisms along the surface of the crown prism. The edges were made parallel by adjusting the flint prisms until the spectra produced by the two sides of the biprism were in line and were as close

together as possible. The lines were made equidistant by moving the flint prism, keeping the lines b and c always in the same direction, until interference fringes produced by the biprism became as clear as possible with a white-light source.

Tests of the Biprism

After the biprism had been assembled the deviations which it produced for light from a mercury arc were measured and the fringe-widths calculated. They were found to be a trifle less than 5×10^{-3} cm, probably because the alignment of a, b and c was not quite perfect. However, the relative values were in good agreement with the calculated ones and since this is the important point no changes were made in the adjustment. The biprism was then used to measure the angular width of a spectrometer slit placed several meters from it. The slit was illuminated by light from a tungsten-filament lamp. A series of observations in which the slit subtended angles of 5×10^{-5} to 8×10^{-5} radians gave an average deviation from the width of the slit as measured with a comparator of about 1 percent.

The present mounting is not well fitted for making astronomical observations. However, it seemed advisable to make a few preliminary observations to see if any unexpected difficulties would arise, before changing the apparatus. The 12½-inch refractor at Columbia University was made available for this work by Dr. J. Shilt. During the time available, there were very few clear hours, but good fringes were obtained with a number of bright stars. Measurements on the double star λ Ophiuchi yielded a separation of 0.36 second. Wilson[3] measured the separation in 1935 and obtained 0.38 with an interferometer and 0.47 with a micrometer. The agreement between his values and those found with the biprism is sufficiently close considering that the biprism observation was taken on a single night and without the most careful setting for position angle. The results obtained thus far indicate that the instrument is capable of giving good results and is worthy of a more extended test. Further work awaits the construction of a new mounting capable of rotation about the line of sight.

Appreciation is expressed to Dr. J. A. Anderson for his encouragement and for his permission to use the 12-inch reflector at the California Institute for some early experiments with an ordinary biprism, and to Dr. J. Shilt and the other members of the Department of Astronomy at Columbia University for their cooperation.

[3] R. H. Wilson, J. Frank. Inst. **221**, 65 (1936).

Necrology

Arthur G. Stillhamer

PROFESSOR ARTHUR G. STILLHAMER died at Bloomington, Illinois, February 5, 1936. Mr. Stillhamer was born at Bloomington, Illinois, February 26, 1878. He received the degree of B.S. from Illinois Wesleyan in 1898 and the A.M. in 1900. During his undergraduate period of study, he was assistant in chemistry and physics. For a year or two following his graduation from Illinois Wesleyan, he was engaged in commercial work. Later, he entered the Graduate School of the University of Chicago in which he was fellow from 1903 to 1905. After a year, 1905–06, as assistant in astrophysics and director of solar research at the Yerkes Observatory, Mr. Stillhamer became, respectively, associate professor of physics and then professor of physics at the Illinois Wesleyan University. In 1910 he again entered industrial work as research physicist and electrical engineer.

Mr. Stillhamer became an associate life member of the Optical Society in May, 1923, and at the annual meeting on October 24 of the same year was transferred to regular life membership. He was also a member of the American Physical Society, the American Association for the Advancement of Science and life member of the American Meteorological Society and a fellow of the Royal Astronomical Society. One of his fields of investigation was the development of means of automatically recording atmospheric transparency.

Norman Macbeth

MR. NORMAN MACBETH died in the Champlain Valley Hospital, Plattsburg, New York, on September 2, 1936, after a short illness.

Born in Stayner, Ontario, September, 1873, Mr. Macbeth devoted his entire life to the general field of illumination and illuminating engineering. For many years he was president of the Macbeth Daylighting Company, Inc., and for some time specialized in the design and manufacture of equipment for the artificial reproduction of daylight. His work in this field was that of a pioneer. He was granted a number of patents covering new developments in artificial daylighting to meet the needs of the dyer of textiles, the expert color worker in dyes and pigments, the examiner of silk, the lithographer and color printer and the wholesale and retail distributors of merchandise and wearing apparel.

In 1907 he developed special arc lamps for photo-engravers' use and, in 1910, the high current density white flame arc lamp for photographic work.

Among his other inventions and developments may be mentioned, the "Amber Light" Welsbach mantle, a mantle without excess green; a circular slide rule especially adapted for illuminating engineering calculations, the Macbeth illuminometer, a portable instrument primarily for commercial use; a "daylight photometer," an instrument for making measurements on color and intensity of artificial and natural light. He was also widely known as an expert consultant on matters pertaining to the general field of industrial lighting.

Mr. Macbeth was a frequent contributor to the literature of illumination and illuminating engineering and from 1912 to 1917 he was editor and owner of the *Lighting Journal*, the only publication in this country devoted exclusively to the advancement of the lighting industry. This journal was combined with the *Electrical World* in 1917.

Mr. Macbeth was one of the charter members of the Optical Society of America and served as member of the Council of the Society from 1916 to 1918. He was a frequent attendant at the meetings of the Society. He was one of the founders of the Illuminating Engineering Society and held many prominent positions in that society, being president in 1927. From 1934 until the time of his death, he was one of the Society's representatives on the Inter-Society Color Council. He was a corresponding member of the Illuminating Engineering Society of London. He also served as member of various boards and committees concerned with the progress and development of illumination.

Proceedings of the Twenty-First Annual Meeting of the Optical Society of America

NEW YORK CITY, N. Y.

October 29–31, 1936

THE twenty-first annual meeting of the Optical Society of America was held at the Hotel Pennsylvania in New York City, October 29 to 31, 1936. In celebration of the fifth anniversary of the founding of the American Institute of Physics, this meeting was held as a joint meeting of all member societies of the Institute.

The program Thursday morning was a symposium sponsored by the American Association of Physics Teachers on Training of Physicists for Industry, D. L. Webster presiding. After introductory remarks by John T. Tate of the University of Minnesota, it was discussed:

1. **From the Point of View of the Educator,** by HOMER L. DODGE, *University of Oklahoma;*
2. **From the Point of View of the Employer,** by A. R. OLPIN, *Kendall Mills.*

On Thursday afternoon the program was the first part of a symposium on Physics in Industry arranged by the Advisory Council on Applied Physics, F. K. Richtmyer presiding. The papers presented were:

1. **What the Industrial Physicist Has Accomplished in the Glass Industry.** E. C. SULLIVAN, *Corning Glass Works.*
2. **Physics in the Metals Industry.** ZAY JEFFRIES AND E. Q. ADAMS, *General Electric Company.*
3. **Let the Physicist Change Your Oil.** PAUL D. FOOTE, *Gulf Research and Development Company.*
4. **Vibration in Industry.** J. P. DEN HARTOG, *Harvard University.*

On Friday morning the symposium on Physics in Industry was continued, the papers presented being:

1. **Building—The Forgotten Child of Physics.** JOHN ELY BURCHARD, *Bemis Industries, Inc.*
2. **A Problem in Communication—The Evolution of the Crystal Wave Filter.** O. E. BUCKLEY, *Bell Telephone Laboratories.*
3. **The Physicist Gets Air Minded.** CLARK B. MILLIKAN, *California Institute of Technology.*
4. **Some Problems in the Electrical Power Industry.** JOSEPH SLEPIAN, *Westinghouse Electric & Manufacturing Company.*

For the remainder of the meeting each of the member societies held separate simultaneous sessions.

At the session of the Optical Society of America Friday afternoon, the program was a symposium of invited papers on Application of Optics in Modern Science. The papers presented were:

1. **The Search for High Efficiency Light Sources.** SAUL DUSHMAN, *General Electric Research Laboratory.*
2. **Optics and the Textile Industry.** E. R. SCHWARZ, *Massachusetts Institute of Technology.*
3. **Application of Optics in Medicine.** MAGNUS GREGERSEN, *University of Maryland.*

On Friday evening there was a joint dinner for members of all the member societies, John T. Tate presiding. Karl T. Compton of the Massachusetts Institute of Technology spoke briefly on What is Ahead in Physics. This talk was followed by entertainment by John Mulholland, President of the Society of American Magicians.

A brief business session of the Society was held Saturday morning, October 31, President Hardy presiding. The secretary and treasurer presented their annual reports for 1935* and discussed informally the changes since January 1, 1936. The treasurer reported that by discontinuing the purchase of subscriptions to the R. S. I. the finances of the Society were in good shape and the secretary noted that the membership of the Society was again increasing.

The rest of the day was given over to the reading and discussion of contributed papers. The authors abstracts of these papers are appended.

MEETINGS OF THE BOARD OF DIRECTORS

Sessions of the Board of Directors were held on Wednesday morning and evening, October 28. The minutes of this meeting are appended.

L. B. TUCKERMAN, *Secretary*

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* Printed in the J. O. S. A. **26**, 298–299 (1936).

Minutes of the Eighth Meeting of the Directors of the Optical Society of America, Incorporated

NEW YORK CITY, N. Y., OCTOBER 28, 1936

BESIDES the transaction of routine business, the following items of general interest to members of the Society were taken up:

Announcements by Secretary

Election of Representatives:

1. Member of Governing Board of the American Institute of Physics. W. B. Rayton elected at meeting of Institute on February 21, 1936.
2. Representative on the Division of Physical Sciences of the National Research Council. L. B. Tuckerman elected executive member and member of Executive Committee, May 3, 1936.

Meetings in 1937

The Directors felt that in view of the two joint meetings in 1936 it was not desirable to hold a joint meeting in 1937. It was voted

"That the Committee on Meetings and Programs be requested to plan a meeting early in March, preferably at Corning, New York, provided satisfactory arrangements could be made."

"That the Committee on Meetings and Programs be requested to find if satisfactory arrangements can be made for a meeting at the Lake Placid Club not too late in October and, if this cannot be arranged, that they consider the possibility of some other resort hotel."

Membership

The secretary's report showed that since the last meeting of the directors twenty new members had been elected as of January 1, 1936, and five new members as of January 1, 1937.

The secretary reported two deaths since the February meeting.

Transfer from Associate to Regular Membership

The following were transferred from associate to regular membership:

ROBERT J. BEITEL, JR. (1032 R)
PAUL BOEDER (1031 R)
LEE A. DUBRIDGE (1006 R)
JOHN R. DUNNING (845 R)
ALFRED N. GOLDSMITH (1046 R)
GEORGE GRAHAM HARVEY (975 R)
GERALDINE WALKER HAUPT (1005 R)
ERNST A. HAUSER (1051 R)
R. M. HOLMES (965 R)
ARTHUR W. KENNEY (934 R)
EDWIN H. LAND (1045 R)
ROGER P. LOVELAND (1001 R)
ROBERT R. MCMATH (1056 R)
J. L. MICHAELSON (1003 R)
W. E. KNOWLES MIDDLETON (1040 R)
NORA MAY MOHLER (1059 R)
CHARLES A. MORRISON (982 R)
GERALD KENT NEELAND (974 R)
EDWARD ROBINSON SCHWARZ (1041 R)
CONRAD A. STONE (1057 R)

Appointment of Associate Editors of The Review of Scientific Instruments

The following associate editors of *The Review of Scientific Instruments* were appointed for a term ending December 31, 1942, as follows:

J. A. BECKER
J. C. BOYCE
J. R. COLLINS
L. A. DUBRIDGE
G. P. HARNWELL
A. H. PFUND

Publication of Index

The Editor reported the publication of the Cumulative Index of the Journal of the Optical Society of America which had been sent to all members of the Society in good standing and was on sale to others at a price of $2.00.

Financial Support of the U. S. National Committee of the International Commission on Illumination

In view of the fact that the cooperation of members of the Optical Society in the work of the Commission represented one of the most useful fields of the Society's activity it was voted

"That the Optical Society of America make an annual contribution of $100 to the U. S. National Committee of the International Commission on Illumination in support of its work."

Report of Colorimetry Committee

The chairman of the Colorimetry Committee stated that much progress had been made in the preparation of the new report of this committee and it was expected that the manuscript would be completed within about four or five months.

Discontinuance of Purchase of The Review of Scientific Instruments

Mr. Kurtz, as chairman of the Finance Committee, reported that the finances of the Society did not permit the continuation of sending *The Review of Scientific Instruments* free to members of the Society. It was voted

"That with the end of the year 1936 the Optical Society of America discontinue the purchase of *The Review of Scientific Instruments* for its members."

In the discussion of this action it was voted

"That the President appoint a committee to consider the editorial policy of the *Journal*, in particular the possibility of changes being desirable in view of the discontinuation of any direct connection of the Optical Society with *The Review of Scientific Instruments*."

Representative on Governing Board of American Institute of Physics

The nomination of E. C. Crittenden for the term February, 1937 to February, 1940 was approved.

Cooperation with American Institute of Physics in Handling Routine of Secretary's Office

The Directors approved tentative plans by which the American Institute of Physics will handle the routine of maintaining an address list and mailing out notices to members.

L. B. TUCKERMAN, *Secretary*

Program of Sessions for Contributed Papers

(TITLES AND ABSTRACTS OF PAPERS)

1. The Color of Water.* KASSON S. GIBSON AND HARRY J. KEEGAN, *National Bureau of Standards.*

At the request of Dr. N. E. Dorsey[1] the authors have computed the trichromatic coefficients of water at various thicknesses. For this purpose the spectral absorptive data of Ashkinass, Aufsess, and Ewan have been used, as published in the International Critical Tables,[2] together with various data by Hulburt[3] and Dawson and Hulburt.[4] In spite of the rather large discrepancies among the various absorptive data, the computed colorimetric values all show that up to a thickness of about 20 meters the color of water is definitely blue-green, the hue being most similar to that of the spectrum at approximately 490 mμ and the saturation (strength) increasing with the thickness. This result is to be expected qualitatively as a result of the relatively strong absorption of water in the red part of the spectrum.

At increasing thicknesses the absorptive data are so uncertain and divergent, due to the extremely low absorption of water in the measured thicknesses, that the computed values have far less significance. At 400 or 500 meters the computed colorimetric values are in each case closely like those of the spectrum at the observed wavelength of minimum absorption; this varies from about 460 mμ (Ewan's data) to about 535 mμ (Ashkinass' data). It is of interest to compare these results with Beebe's observations on sea water.[5] ". . . Finally, at 800 ft. the spectrum showed to the eye pale grayish-white. . . . The brightness was very low and all ability to appraise the hue was gone. . . . It was a very narrow area, not far from the middle of the spectrum, about the 520th wave line, blurred, fading out toward the violet end, and much more abruptly toward the red end. Yet, when I took my eye from the spectroscope, and looked out and down, I saw only the deepest, blackest blue imaginable, a color which in the spectrum had vanished four hundred feet above. . . ."

* The present paper will appear in full in J. Research Nat. Bur. Stand.
[1] Properties of the ordinary water substance; ms. in preparation.
[2] Int. Crit. Tables, Vol. 5, p. 269, 1929.
[3] J. O. S. A. **22**, 408 (1932).
[4] J. O. S. A. **24**, 175 (1934).
[5] Bull. N. Y. Zool. Soc. **33**, 201 (1930).

2. Colorimetry of the Blue Arcs of the Retina.* SIDNEY M. NEWHALL, *Johns Hopkins University.*

The blue arc phenomenon, elicited by averted vision of a strip stimulus on a dark ground, was "specified" by matching to it the known additive mixture of a special trichromatic colorimeter. Typical arcs were found to lie in the near-violet purple region of I.C.I. color space, with dominant wave-length 566c mμ, brilliance that corresponding to 0.75 foveal photon, and excitation purity 75 percent. The chromaticity and brilliance of the phenomenon appeared to be relatively though not wholly independent of the stimulus. The precision of the method is about 0.1 that of usual colorimetry of "external" phenomena, but there are various possibilities of refinement and application.

* The present paper will be submitted in full to J. O. S. A.

3. Tri-Dimensional Analysis and the Non-Film Modes of Color Appearance. HARRY HELSON, *Bryn Mawr College.*

Since the work of Katz[1] it has been known that the classical description of colors in terms of hue, tint and saturation is adequate only for film colors (colors seen through slits or other small apertures). Tri-dimensional analysis with specification by means of trilinear coordinates, while completely adequate for film colors, fails to account for colors seen in unrestricted vision where even the fundamental dimensions may be completely altered. For example, three samples having identical trilinear coordinates may, when viewed as surface colors, appear quite different, *viz.*, one may be red, one neutral, and the third, green, to mention only the case of three non-selective samples of high, medium and low reflectance, respectively, viewed in red light. Inadequacy of trilinear specification for non-film colors will be demonstrated by converting film to surface colors; by consideration of attributes of color ignored in the classical analysis; and by including various factors commonly neglected. These inadequacies cannot be overlooked either in any general theoretical consideration of color, nor in the interests of better practise. Based on preliminary observations by Judd[2] and on more extended work at Bryn Mawr, a beginning has been made toward adequate quantitative and qualitative generalization whereby the transition from film to surface colors can be predicted. But a large field remains which will be indicated by brief reference to the various modes of color appearance described by Katz and others.

[1] David Katz, *The World of Colour* (Kegan Paul, Trench, Trubner and Co., London, 1935).
[2] D. B. Judd, "Surface Color," J. O. S. A. **25**, 44 (1935).

4. Psychophysical Descriptions for Families of Spectrophotometric Stimuli: Essentially Increasing the Usefulness of Spectrophotometric Specifications. LESTER C. LEWIS, *Mead Corporation.*

The use of spectrophotometric specifications for many colored materials is encouraged greatly when one is able to recognize instantly the correspondence between these and more familiar psychophysical specifications. The present paper sketches a survey of this mapping problem.

To a single "color" specified, for instance, by the 1931 I.C.I. coordinate system there correspond, of course, an infinity of spectrophotometric stimuli. Suppose, however, we deal with industrial products colored by a limited number of constituents with limited variation in their spectrophotometry. Families of spectrophotometric curves are obtained with rather simple relations. These correspond to simple psychophysical relations: and insofar as these latter are familiar to the non-physicist create confidence in spectrophotometry.

The present work originated in the field of near whites—particularly of nearly white papers. It has been found useful to assume simple spectrophotometric variations from a standard (such as an increase in reflectance proportional to wave-length increment throughout the spectrum), calculate the I.C.I. coordinates; and hence map the spectrophotometric region on a color triangle region. General laws for this mapping are investigated; laws for the addition of small spectrophotometric increments, etc. A large class of spectrophotometric curves result in constant chromaticity. Another class of great interest results from calculating by the Kubelka-Munk[1] theory of diffusing media the spectrophotometric data for a varied "depth" of dyeing. It is felt that from these beginnings will arise a demand for a very comprehensive set of maps.

The advances of the past ten years in spectrophotometry, together with the advantages of agreement upon the I.C.I. system are leading to "new" colors. The work of MacAdam[2] on "visual efficiency of colored materials" is an example; and the work of Nolan and Van den Akker on what might be called "synthetic" colors (i.e. produced by templates over the spectrum). Mapping spectrophotometric data by families should further this progress.

[1] Kubelka and Munk, "Ein Betrag zur Theorie der Farbanstriche," Zeits. f. tech. Physik **12**, 593 (1931).
[2] MacAdam, "Theory of the Maximum Visual Efficiency of Colored Materials," J. O. S. A. **25**, 249 (1935); Maximum Visual Efficiency of Colored Materials, J. O. S. A. **25**, 361 (1935).

5. Goniophotometric Data on Gloss Differences. RICHARD S. HUNTER, *National Bureau of Standards and George Washington University.*

This paper is one of a series dealing with the subject of gloss measurement. A problem in gloss measurement may be usually stated as follows: given a series of samples which exhibit differences in glossiness, the problem is to devise satisfactory reproducible methods of measurement for determining the differences in glossiness.

Goniophotometric data, which are descriptions of the manner in which surfaces direct reflected light,[1, 2, 3] furnish a means for studying the reflecting properties responsible for glossiness. It is the purpose of this paper to present goniophotometric data which have been obtained on representative surfaces exhibiting different types of glossiness. The types of glossiness may be identified by means of descriptions previously published by the author.[4] In the case of each gloss type represented, the possibilities for simple photometric measurements of gloss will be pointed out. By thus examining the results of goniophotometric analyses, it is hoped to provide a method by which the photometric designs of simple gloss-measuring devices may be based directly on observed differences in glossiness. Hitherto most of the photometric designs of simple gloss meters have been devised by wholly arbitrary methods.

The apparatus employed was designed and built by McNicholas[5] and has since been improved by the inclusion of a photo-cell and slits to give the instrument high angular resolving power.

[1] L. A. Jones, J. O. S. A. **6**, 140 (1922).
[2] H. J. McNicholas, Bur. Standards J. Research **1**, 29 (1928); RP3.
[3] Ries and Gilbert, Proc. A. S. T. M. [II] **30**, 911 (1930).
[4] R. S. Hunter, Scientific Section Cir. 493 of the Nat. Paint, Varnish and Lacquer Assoc., Oct. 1935.
[5] H. J. McNicholas, J. Research Nat. Bur. Standards **13**, 211 (1934); RP704.

6. The Visibility of Radiant Energy at Low Intensities. K. S. WEAVER, *Eastman Kodak Company.* (*Introduced by Loyd A. Jones.*)

A visibility curve depending on about 15 observers has been taken at an intensity comparable to the lowest used in darkroom work.

A series of determinations of the wave-length of maximum visibility for several intensities and observers has also been made giving a curve extending from near the dark adapted threshold to about 2 foot-lamberts.

The observations were all made with the natural pupils and binocular vision.

Comparisons with some previous work of other authors are made.

The wave-length of maximum visibility at the highest intensity corresponds very closely with that of the standard I.E.S. photopic curve. At the lower levels, values are found approximating those given by König[1] in his complete curve, and by Hecht[2, 3] for an intensity 2.7 times the dark adapted threshold.

[1] P. G. Nutting, "The Visibility of Radiation, A Recalculation of König's Data," Bull. Bur. Standards **7**, 235–238 (1911).
[2] S. Hecht and R. E. Williams, "The Visibility of Monochromatic Radiation and the Absorption Spectrum of the Visual Purple," J. Gen. Physiol. **5**: 1–33 (1922).
[3] Louise L. Sloan, "The Effect of Intensity of Light, State of Adaptation of the Eye, and Size of Photometric Field on the Visibility Curve," Psychological Monographs **38**, No. 1 (1928).

7. Photometric Discrimination with a Diffuse Boundary. W. E. KNOWLES MIDDLETON, *Meteorological Service of Canada.*

A knowledge of the threshold of contrast when the boundary between the two parts of the field is diffuse is of importance in the theory of the visual range in fog. An apparatus has been set up to produce a photometric field of this type, in which the transition from one brightness to the other follows the diffusion function.

The results are presented as the greatest allowable diffusion for the perception of a given contrast, the diffusion being measured in minutes of arc from the line where the brightness begins to decrease to the line where it has fallen to 1/100 of the original difference.

For two independent observers, it was found that diffusion had little effect on the threshold of contrast up to 5 or 8 minutes of arc, but that with greater diffusion there was a linear dependence of contrast threshold on diffusion up to about 30′, when readings became difficult. This was for a field surrounded by a dark background. For a gray background about $\frac{1}{3}$ as bright as the field, the relation remains linear, but the contrast threshold is affected by somewhat less diffusion and also varies more rapidly as the diffusion increases.

8. A Photometric Comparison of Absorption Lines.* A. A. FROST, D. W. MANN, AND O. OLDENBERG, *Research Laboratory of Physics, Harvard University.*

For the purpose of chemical analysis, concentrations of gas molecules are observed by the intensity of their *absorption* spectrum rather than by the intensity of their *emission* spectrum. The various rotational lines of a molecule represent concentration marks on each exposure of an absorption spectrum. If the temperature of the gas is known, the relative values of concentration can be evaluated from the theory of band spectra. Hence by matching the lines of two exposures taken with different concentrations, one can determine the relative values of concentration. An instrument was constructed in which two plates (or cuts from the same plate) can be projected through separate objectives. A pair of mirrors (sides of a 90° prism) on this instrument permits examination of the two halves of the same field of view with one eyepiece. When the illumination of the two plates is adjusted so that both continuous backgrounds appear with the same intensity, one can observe accurately which absorption lines show the same intensity. This photometric device helps in tracing the progress of a fast gas reaction by the intensity of absorption spectra of radicals, like OH, taken in snapshots.

* The present paper will appear in full in J. O. S. A. or R. S. I.

9. A High Speed, High Precision Microphotometer of New Design. R. A. SAWYER AND H. B. VINCENT, *University of Michigan.*

A new non-recording microphotometer has been designed to provide the high speed combined with high precision demanded in the application of spectrographic analysis to metallurgical process control. The source is a straight filament lamp made for the purpose in this laboratory. The filament is imaged on the fore-slit by an f : 1.5 anastigmat camera lens of 1-inch focus lens. A combination of two 2-inch f : 1.5 lenses images this fore-slit on the photographic plate and the light which passes through the plate falls directly on a photo-voltaic cell. This optical system provides maximum brilliancy and compactness.

The plate is mounted on two slide systems at right angles which permit adjustment in any direction. To view the plate during adjustment the cell may be thrown out of the field and a beam spreading lens swung under the plate illuminating a larger area of the plate, which is then imaged by a projection lens on a screen above the plate. When adjustment is complete a foot treadle throws out this auxiliary lens, returns the cell to position and engages a motor driven clutch which draws the line across the image of the fore slit in 3 sec. The galvanometer has a period of 1 sec. and its maximum deflection is read on a translucent scale above the instrument. The cell has so little zero drift, dark current and temperature effect that the zero or dark reading of the galvanometer is permanent and need not be repeated during observations. The dark-full light deflection is about 500 mm. The speed of adjustment and operation is such that a single observation on each of 6 lines may be made in one minute with less than 1 percent error.

10. An Electro-Scopometer for Calibration and Comparison Measurements of Light Absorption.* WILLIAM G. EXTON, M.D., *Prudential Insurance Company.*

The photoelectric scopometer[1, 2, 3] has proved so satisfactory that it has been re-designed to provide a comparison measurement in addition to its original calibration measurement. As this flexibility fills every conceivable demand of the laboratory, one is no longer compelled to resort to visual instruments when comparison measurements are preferable or indispensable.

The new scopometer consists of an optical axis with light source in the center, specimen pockets symmetrically on each side and a photo-emissive tube on each end forming the variable arms of a Wheatstone bridge. The only movable parts are controlled by two dials with attached scales. Turning one changes the area of a variable aperture in front of the left photo-tube. Turning the other moves the lamp in the optical axis.

For calibration measurements the instrument is balanced on the null point of the galvanometer by moving the lamp, unbalanced by interposing samples in the right cup, and balanced again with the calibrated variable aperture. The concentration equivalents of the scale readings at this point are then found on a predetermined calibration.

For comparison measurements the instrument is balanced on the null point of the galvanometer with the variable aperture, unbalanced by interposing standards and samples in the right cup, and balanced again by changing the position of the lamp. The concentration equivalents of the scale readings at this point are then found by solving a simple straight line equation.

After briefly discussing light absorption measurements in medical laboratories the construction and operation of the scopometer are described and its characteristics and varied applications illustrated by data.

* The present paper will appear in full in J. O. S. A. or R. S. I. From clinical standpoint in Am. J. Clin. Path.

[1] Wm. G. Exton, "Electro-Scopometry," J. O. S. A. **21**, 146 (1931).

[2] Wm. G. Exton, "The Present Status of Clinical Laboratory Measurements with a Note on the Photo-Electric Effect," Am. J. Clin. Path. **1**, 237–250 (1931).

[3] Wm. G. Exton, "The Photo-Electric Scopometer," Am. J. Clin. Path. **2**, 411–420 (1932).

11. Schleiermacher Equations and First-Order Laws in General Optical Systems.* M. HERZBERGER, *Kodak Research Laboratories.*

The difference between the Bruns Hamilton form of optical equations and the Schleiermacher form is sketched. A survey is given of the different types of optical systems according to Gullstrand and the different types of image formation for a given object point. What can be achieved by choosing suitable coordinate origins and coordinate planes? Standard forms of the Schleiermacher equations for the different types are given and special interesting laws are discussed.

* The present paper will appear in full in J. O. S. A.

12. Analytical Search of the Hyperbolic Reflector for Fresnel's "Most Useful Effect." L. E. DODD, *University of California at Los Angeles.*

In Fresnel's analysis of the parabolic reflector, considering finite size of source he defined a quantity which he called the useful effect (l'effet utile).[1] The amount of reflected light is proportional to the differential solid angle between reflector and source, for any given point on the reflector. Furthermore, the dispersion of the extreme rays is less the greater the distance from the source. This distance he combined with the differential solid angle in an expression proportional to both of these. Integration then gave the formula for the useful effect, a function of the latus rectum of the parabola and the depth of the reflector. The "most useful effect" is present when this function is a maximum. Even though he had to deal with only one parameter, it was necessary to make successive approximations for his final numerical result.

The present paper applies Fresnel's test to the hyperbolic reflector, where the least possible number of parameters is two. It was found possible to show mathematically that for the hyperbola the useful effect reaches no maximum except for degenerate cases.

[1] D'Augustin Fresnel, *Oeuvres complètes* (Paris 1870), Vol. 3, p. 41.

13. Electrically Operated Welsbach Lamp.* A. H. PFUND, *Johns Hopkins University.*

This lamp is to serve as a source of radiation from the visible into the far infrared. The heating unit consists of sheets of ashed Welsbach mantle, heated by the arc discharge formed between terminals connected to the secondary of a high potential transformer. When operated in air, a small, pointed gas-flame is allowed to play on the mantle, thus steadying the discharge and increasing the temperature. For the near infrared (0.7μ to 15μ) both gas and electricity are used whereas, for the far infrared (15μ to 150μ) gas heating alone is employed. When the lamp is operated in a partial vacuum, variations in spectral distribution are effected, largely, by working at different pressures. At pressures around 10 cm the emission is essentially that of the gas-heated Welsbach while, at pressures around 25 cm the emission rivals that of a Nernst lamp in the near infrared.

* The present paper will appear in full in J. O. S. A.

14. A Quartz Mercury Arc with Electrodes of Low Work Function. WILLIAM T. ANDERSON, JR. AND LESTER F. BIRD, *Ultraviolet Research Laboratory, Hanovia Chemical & Mfg. Co.*

Early attempts of Konen and Jungjohann[1] and of Henri George[2] to make quartz mercury arcs with solid incandescent cathodes were only partially successful, because their cathodes had too high a work function or were not properly proportioned to function at correct operable temperatures.

The authors have found that the variations in thermal conductivity with temperature of some inorganic oxides might be a useful characteristic to employ in the construction of such an electrode. They have employed these oxides in a laminated structure together with Wehnelt activation in order to provide an automatic temperature control for the arc cathode. The arrangement provides the necessary rapid temperature increase required for such an electrode almost immediately after the arc has been struck, and prevents the temperature of the electrode from exceeding a destructive value.

Employing these electrodes and a filling of rare gas and a small quantity of mercury, they have made self-lighting high pressure quartz mercury arcs operable directly on alternating current and with simplified electrical controls. The electrical characteristics of their lamp are discussed.

[1] Konen and Jungjohann, Verh. deutsch. Phys. Ges. **3**, 145 (1910).
Henri George, U. S. Patent 1,361,710, Dec. 7, 1920.

15. Brightness of Cathodo-Luminescence at Low Current Densities and Low Voltages. THOMAS B. BROWN, *George Washington University.*

A discharge tube has been designed which produces quite uniform electron bombardment of a fluorescent target over a circular area of about 2 cm^2, for potentials varying from 1400 volts down to below 200 volts. Secondary electrons arising from the accelerating electrodes are eliminated by suitable radial electrostatic fields so that the electrons arrive at the target all with the same speed. In former work there has always been some uncertainty as to the potential at the surface of the fluorescent substance. In the present work it is shown that when this surface is very carefully shielded electrostatically, secondary emission from it will maintain its potential to within one or two volts negative of the potential of the shield.

With artificial willemite without any binder, it is found that for sufficiently low current densities, J, and voltages, V, the brightness of fluorescence, B, is proportional to JV^3. For higher current densities B increases less rapidly than does J and the constant voltage curves approach those obtained for commercial cathode-ray tubes. Above approximately 800 volts B increases somewhat more rapidly than does V^3. There is no indication of a measurable "threshold" voltage for this material. Fluorescence is measurable down to 140 volts, at which voltage the fluorescent surface *abruptly* charges up. This peculiar phenomenon is discussed in some detail.

The power supply is stabilized, and voltages are measured by a high resistance voltmeter. The brightness is measured visually, the comparison lamp being color-matched with the fluorescence.

Comparison of these results is made with those of other investigators.

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H. W. Ernst, "Excitation of Phosphorescence by Cathode Rays," Ann. d. Physik **82**, 1051–76 (1927).

L. Levy and D. W. West, "Fluorescent Screens for Cathode Ray Tubes," J. I. E. E. **79**, 11–19: Disc. 25–32, July (1936).

16. Fluorescent Light Microscopy—A New Method in Colloid Physical Research. E. A. HAUSER AND C. J. FROSCH, *Massachusetts Institute of Technology and Bell Telephone Company.*

An historical introduction of the development of ultraviolet light microscopy with special reference to fluorescent light microscopy is given. The theoretical and practical difficulties encountered in constructing ultraviolet light sources of sufficient intensity and concentration to produce sufficiently intense fluorescence for microscopic work are enumerated. The value of the iron arc as a light source as developed by Haitinger is critically discussed. A theoretical discussion of the major differences between normal and fluorescent light microscopy and the optical limitations of the latter method are pointed out. The application of fluorescent light microscopy in visually studying adsorption and related surface phenomena qualitatively is described. It is shown that interfacial reactions can be *visually* demonstrated by the changes in florescence at the interface. In the case where we are dealing with capillary active substances exhibiting pronounced fluorescence the adsorption or concentration of these substances in the surface of the solute is demonstrated and any changes in the rate of adsorption or concentration in the interface are directly observed. Processes of emulsification are studied permitting an immediate visual differentiation between the possible types of emulsions. The influence of emulsifying agents and their actual distribution throughout the system is demonstrated. The conditioning of solid surfaces as the basis for differential flotation processes is visually demonstrated.

Differences in the mechanism of the spreading of films on liquids with fresh or aged surfaces can now be microscopically followed if one of the components shows pronounced fluorescence. Dehydration of hydrophillic colloids (coagulation) is visually observed by the decrease in thickness of the hydrated layers. In cases where none of the components exhibits a satisfactory fluorescence of its own it is possible to make use of solutions of certain chemicals exhibiting pronounced fluorescence, so-called "fluorochromes." The possibility of making quantitative measurements in fluorescent light microscopy by the use of appropriate instruments, e.g., microspectrographs or photometer-oculars is referred to. Suggestions for possible application of this new technique in scientific colloid physical research will be made.

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Mikrochemie, M. Haitinger, IX, 220, 430 (1931) "Farbmessungen."

Theoretische Grundlagen u. Anwendungen, Edward Hatschek and Max Haitinger (Emil Haim and Co., 1936).

17. Glass Color Filters for Special Applications.* H. P. GAGE, *Corning Glass Works.*

In preparing glass color filters for special applications, the scientific glass maker may go through a series of mathematical calculations but must interpret these on the basis of the glass maker's experience. To illustrate this the design and manufacture of a glass color correcting filter for the Weston Photronic cell is given as an example. The spectral transmission of any thickness of a glass can be calculated from known spectral transmission and thickness of a measured piece by the aid of a special table derived from an anti-logarithm table showing the logarithm of (transmission divided by 0.92) or by the use of a slide rule. This is the only calculation which can strictly be relied upon as variations of transmission with variations in concentration of the coloring agents dissolved in glass are likely to deviate considerably from Beer's law.

Specific example: correction of the Photronic cell: given the spectral response of the Photronic cell and the curve of the luminous response of the eye, the curve for the theoretical filter can be calculated. Actual filters were made by combining a yellow glass filter with a blue green filter made in a special type of glass. The calculation of the thickness of the two filters is made by solving two simultaneous equations in the logarithmic form and results in a corrected photronic cell whose accuracy of response to radiation from tungsten lamps operated at various color temperatures and to such peculiar spectral distributions

as the mercury arc, sodium arc, and the neon tubes, is comparable to that of present day practice in heterochromatic photometry.

* The present paper will appear in full in J. O. S. A.

BIBLIOGRAPHY

M. E. Fogle, "New Color Corrected Photronic Cells for Accurate Light Measurements," Trans. I. E. S. **31**, 773 (1936).

18. A Comparison of Some Filters Absorbing the Violet Lines of Mercury. P. L. BAYLEY, *Lehigh University.*

Spectrophotometric measurements have been made of gelatin films of β-methyl esculetin, and solutions of sodium nitrite, nitrobenzene, *m*-dinitrobenzene, and sodium acetate. Transmission curves of these materials will be compared with those of the Wratten 2A filter and Corning Noviol A glass. W. H. Aughey and W. D. Lansing[1] noted the violet absorbing properties of β-methyl esculetin. The author has studied the making of gelatin films of this compound and has found no method of obtaining accurately reproducible absorbing properties. The best filters obtained are definitely inferior to Corning Noviol A. The Wratten 2A filter seems to be the best filter available for work in Raman spectroscopy when the mercury line λ4358 is used as the exciting source. The uncemented filter may be wrapped around the sample tube between the tube and the water cooling jacket. It transmits better than 80 percent of λ4358 but only about 0.1 percent of λ4046. The stability of the filter will be shown by transmission curves taken at intervals during several hundred hours of exposure to the glass mercury arc under operating conditions in a General Electric Company Raman outfit.

[1] W. H. Aughey and W. D. Lansing, Phys. Rev. **44**, 326 (1933).

19. Statistical Investigation of the Uniformity of Grades of Lovibond Red Glasses.* GERALDINE WALKER HAUPT, *National Bureau of Standards.*

Inconsistences in the grades of vegetable oils[1] arising from the use of Lovibond glasses have created the need for uniformly graded red glasses. As a result, during a period of 8 years, 2700 Lovibond red glasses have been calibrated in combination with Lovibond 35 yellow at the National Bureau of Standards in terms of the standard Priest-Gibson (N'') unit and scale,[2] the additivity of which has been confirmed.[3] Results from a statistical investigation of the first 1000 red glasses[4] showed that important discrepancies could occur in grading oil because of errors in the numerals on the glasses. One-tenth of a unit is taken into account in oil grading and glasses of similar chromaticity were found which had been assigned nominal Lovibond grades, N, differing by a whole unit.

The results of the present investigation on all 2700 glasses confirm the previous departures from additivity, both the important erratic departures and the regular, though smaller, departures. However, individual glasses of the same nominal grade among the last 700 submitted have more nearly the same chromaticity. It may be concluded, therefore, from the data on these 700 glasses that there is less variation among glasses of identical grade, but that the additivity of the scale as a whole is unimproved.

* The present paper will appear in full in J. Research Nat. Bur. Standards.

[1] Harry J. McNicholas, "Color and Spectral Transmission of Vegetable Oils," J. Research Nat. Bur. Standards **15**, 99 (1935); also Oil and Soap **12**, 167 (1935).

[2] Irwin G. Priest and K. S. Gibson, "Standardizing the Red and Yellow Lovibond Glasses," J. O. S. A. and R. S. I. **16**, 116 (1928).

[3] Kasson S. Gibson and Geraldine Walker Haupt, "Standardization of Lovibond Red Glasses in Combination with Lovibond 35 Yellow," J. Research Nat. Bur. Standards **13**, 433 (1934): RP 718; also Oil and Soap **11**, 246 (1934).

[4] Geraldine K. Walker, "Statistical Investigation of the Uniformity of Grades of 1000 Lovibond Red Glasses," Bur. Standards J. Research **12**, 269 (1934), RP 653.

20. An Experimental Study of Binocular Flicker. BRIAN O'BRIEN AND FRED H. PERRIN, *Institute of Applied Optics, University of Rochester.*

An apparatus has been developed for the rapid and precise determination of monocular and binocular critical flicker frequency over a wide range of field sizes and brightness levels and for all phase angles. It has been applied to the study of certain binocular flicker effects first described by Sherrington.[1]

Define (1) simultaneous critical frequency as minimum frequency for disappearance of flicker when both eyes are stimulated and occulted simultaneously; (2) alternate critical frequency, when stimulation and occultation occur alternately; and (3) Sherrington effect, simultaneous frequency minus alternate, which experiment shows to be always positive. For a 2° field with dark surround, equal light and dark periods in the flicker cycle, and abrupt transition (rectangular wave form), the Sherrington effect is a constant fraction (7.6 percent for one observer) of critical frequency over the range of 0.1 to 10,000 Troland photons retinal illumination. For larger fields, the Sherrington effect is substantially independent of field size; for smaller fields, the effect diminishes faster than does the mean critical frequency. The absolute magnitude of the effect is subject to great individual variations, especially for small fields. Furthermore, although the alternate frequency is usually but not always lower than the monocular for most field sizes, it is higher for a $\frac{1}{4}$° field in the case of every one of seven subjects tested; the simultaneous frequency is invariably higher than either of the others.

Preliminary observations using an illumination wave form proportional to $\sin^2 t$ showed a Sherrington effect of the same order of magnitude as that produced by an abrupt transition from light to dark. Thus the effect cannot be due merely to the sudden transfer of energy from one eye to the other.

An explanation of the Sherrington effect based upon association fibers connecting the neural systems of the two eyes appears to be untenable in view of the time relations involved. An explanation based upon partial lateral conduction at the synapses in the external geniculate bodies or the striate cortex is adequate to describe the present experiments and does not conflict with existing neurological evidence. It predicts that the effect should be small or absent when non-corresponding areas of the two retinas are stimulated; when this prediction was tested, the mean value for several observers was found to be only 5 percent of the value for corresponding areas.

[1] C. S. Sherrington, "Binocular Flicker and the Correlation of Activity of 'Corresponding' Retinal Points," Br. J. Psych. **1**, 26 (1904).

21. Problems Concerning the Production of Cathode-Ray Tube Screens. H. W. LEVERENZ, *RCA Laboratory.* (*Introduced by W. F. G. Swann.*)

Calculations and tables are given which are used to determine electron beam penetrations for 100–100,000 volt electrons into several important luminescent materials (i.e., phosphors). An indirect method of finding the secondary emission equilibrium potential of a CR tube screen is described.

Theoretical and practical considerations determining optimum phosphor particle sizes and screen efficiencies are discussed. Illustrative experimental data are given for the application of 2 $ZnO \cdot SiO_2$: Mn (zinc silicate activated with manganese) in the usual type of CR tubes. Information is given regarding a satisfactory means of comminuting oxide phosphors and preparing settling suspensions which allow the settling of uniform and tenacious CR tube screens without resorting to binders. Sulphide phosphors are found to require delicate treatment which restricts their applicability as compared with the more stable oxide phosphors.

22. Bausch and Lomb Dustcounter.* GUSTAVE FASSIN, *Bausch & Lomb Optical Co.*

This instrument takes a grab sample of air one one-thousandth of a cubic foot in volume. The dust is impinged onto a specimen slide, which without removal from the instrument can be examined and the dust particles counted by means of a 200 power dark field microscope built into the instrument. The resulting count multiplied by 100,000 gives the number of particles per cubic foot of air sampled.

Provisions are made for particle size estimation.

* The present paper will appear in full in Industrial Hygiene.

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